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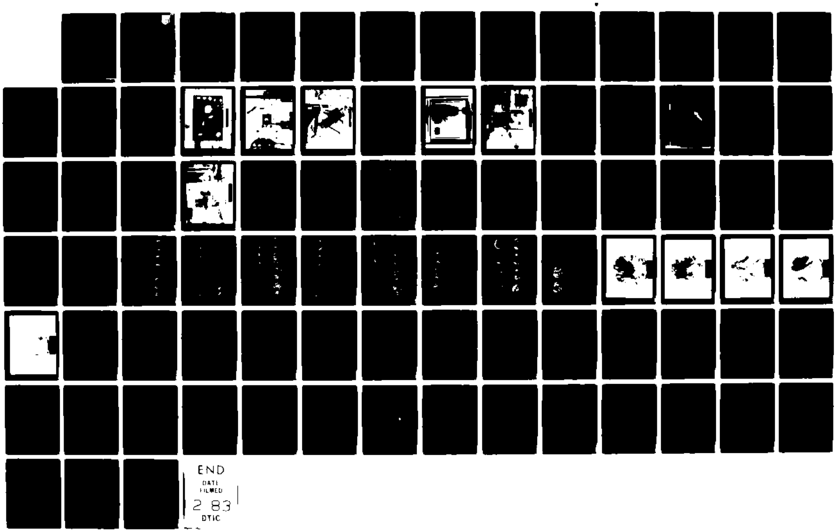

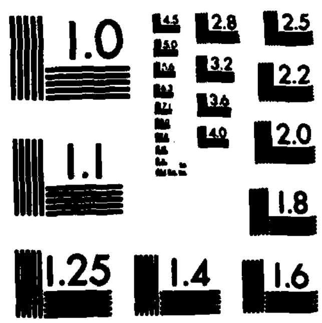

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MULTI-DUCTED INLET COMBUSTOR RESEARCH AND DEVELOPMENT

Universal Energy Systems, Inc.
4401 Dayton-Xenia Road
Dayton, Ohio 45432

October 1982

Interim Report for Period August 1981 to August 1982

Approved for public release; distribution unlimited.

AERO PROPULSION LABORATORY
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This technical report has been reviewed and is approved for publication.

Kenneth G. Schwartzkopf

KENNETH G. SCHWARTZKOPF
Project Engineer

Frank D. Stull

FRANK D. STULL
Chief, Ramjet Technology Branch
Ramjet Engine Division

FOR THE COMMANDER:

JAMES D. JOHNSON, Col, USAF
Ramjet Engine Division
Aero Propulsion Laboratory

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Preliminary flow visualization studies and residence time testing has been conducted of a multi-ducted inlet combustor configuration at the Water Tunnel test rig facility of the Ramjet Technology Branch AFWAL/PORT Wright-Patterson AFB, Ohio. Tests were conducted on a 45 degree inlet configuration for combustor dome plate positions of 0, 1, 2, 3, 4, 5, 6, 7, and 8 inches forward of the inlet ducts. Tests were conducted at water flow rates of 150 to 500 gallons per minute in 50 gallon per minute increments. The inlet duct Reynolds number per foot range was from 0.62 to 2.06 million

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per foot. This initial test program was conducted after the completion of several facility improvements and hardware modifications. In conjunction with the research and development effort, support has also been provided to the Cold Flow Channel and the Burner Thrust Stand test rigs of the Ramjet Technology Branch AFWAL/PORT. A literature survey on related technical areas has been conducted and work has been initiated on math modelling efforts.

PREFACE

The research and development efforts reported herein were performed on Air Force contract #F33615-81-C-2074 for the period covering 31 August 1981 to 31 August 1982. This Interim Report details the tasks accomplished and tests conducted with the multi-ducted inlet combustor configuration in the Water Tunnel test rig facility. The performance of this contract is being monitored by the Ramjet Technology Branch (AFWAL/PORT) of the Aero Propulsion Laboratory Wright-Patterson AFB, Ohio.

These investigations and studies are being conducted to obtain quantitative and qualitative data from the multi-ducted inlet combustor configuration for flow analysis and matematical modeling purposes. The major portion of the support provided to date has been to upgrade and improve the data acquisition capability of the Water Tunnel test rig facility. Only preliminary residence time testing and flow visualization efforts have been conducted. Dr. F. Eastep and Dr. J. Scott, of the University of Dayton, prepared the report on the technical literature survey and mathematical modeling efforts as part of the subcontracting arrangement with Universal Energy Systems, Inc. in support of this program.

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SYMBOL	DESCRIPTION
A	Area
C	Dye Concentration-Unit Volume Per Unit Volume
DP	Dome Position
GPM	Gallons Per Minute
LP	High Intensity Light Position
Q	Quanitiy of Detected Dye
Re	Reynolds Number
t	Time
Δt	Delta Time Increment
u	Fluid Velocity
V	Volts
Vol	Volume
α	Inlet Duct Angle
ρ	Density

SUBSCRIPTS

D	Detector
e	Exit
i	Inlet
o	Initial Condition
r	Residence
T	Total
1	Streamwise Direction
2	Dome Region

SUMMARY

Universal Energy Systems, Inc. has completed the first year of a three year research and development contract to investigate multi-ducted inlet combustor configurations. These efforts are being conducted at the Water Tunnel test rig facility for the Aero Propulsion Laboratory's Ramjet Technology Branch (AFWAL/PORT), Wright-Patterson AFB, Ohio. The objective of this program is to determine correlations between water simulations and actual combustor performance of multi-ducted inlet combustor configurations. Other objectives include the development of mathermatical models to describe internal flow field characteristics and to provide information on expected combustor performance.

Preliminary flow visualization and residence time testing has been conducted of a multi-ducted inlet combustor. Tests were conducted for combustor dome plate positions of 0, 1, 2, 3, 4, 5, 6, 7, and 8 inches forward of the inlet duct and were conducted at water flow rates of 150 to 500 gallons per minute in 50 gallon per minute increments. The inlet duct Reynolds number per foot range was from 0.62 to 2.06 million per foot. These initial residence time tests were conducted after the completion of several facility improvements and hardware modifications. In conjunction with this research and development effort, support has also been provided to the Cold Flow Channel and the Burner Thrust Stand test rigs of the Ramjet Technology Branch AFWAL/PORT.

SECTION 1

INTRODUCTION

The technical information, data, and tests described herein are the results of research and development efforts performed by Universal Energy Systems, Inc. (UES) in support of the Aero Propulsion Laboratories Ramjet Technology Branch (AFWAL/PORT), Wright-Patterson AFB, Ohio. The research and development test program is directed at obtaining both qualitative and quantitative data on fundamental technology problems associated with the multi-ducted inlet combustor. This interim report covers research efforts conducted at the Water Tunnel test rig facility of the Ramjet Technology Branch (AFWAL/PORT) during the contract period 31 August 1981 to 31 August 1982.

The major emphasis of the technical support provided by UES during this reporting period has been to accomplish the upgrading and improvement of support systems of the Water Tunnel test rig facility. These efforts were in preparation for conducting the residence time studies and associated test programs to obtain test data on multi-ducted inlet combustor configurations. These efforts will provide the information necessary to perform flow field analysis and aid in the development of a mathematical model of the multi-ducted inlet combustor configuration.

Included in this report are detailed descriptions of the test facility, Water Tunnel test rig support, technical support of other test rigs and facilities, multi-ducted inlet combustor configuration, instrumentation, test program, data reduction, data presentation, flow field analysis and math modelling efforts, and conclusions and recommendations.

SECTION 2

TEST FACILITY

The Water Tunnel test rig, Figure 1, is a closed loop 1500 gallon per minute water tunnel that is utilized to simulate the internal fluid flow dynamics of ramjet combustor configurations. It is located in Building 18E, Room 22, Wright-Patterson AFB, Ohio. All piping within the Water Tunnel system is of PVC plastic and the test section is constructed of clear plexiglass. The clear plexiglass test section allows for complete observation of test combustor flow fields. The Water Tunnel test rig is capable of testing full scale single and multi-ducted inlet ramjet combustor configurations over inlet duct Reynolds number range of 0.4 to 4.0 million per foot. Simulations of auxillary combustor flows such as gas generators and fuel injectors are also possible. Support systems of the Water Tunnel test rig include an air/dye injection system, a laser/optical detection system, and a high intensity light source.

The air/dye injection system, Figure 2, is capable of injecting air bubbles or colored dye into the combustor configuration for flow visualization or for residence time testing. Injections are made through a variety of specialized probes or test ports. The system can be operated manually or through a precision timer control. Pulse durations of 0.01 second are possible. Dye injections are made through a vernier metering valve to allow for accurate control of the quantity of injected dye.

The laser/optical detection system, Figure 3, consists of a Spectra Physics 0.05 watt Argon laser, two RCA 6655A photomultiplier detector tubes, and various beam splitting and alignment optics. This system is

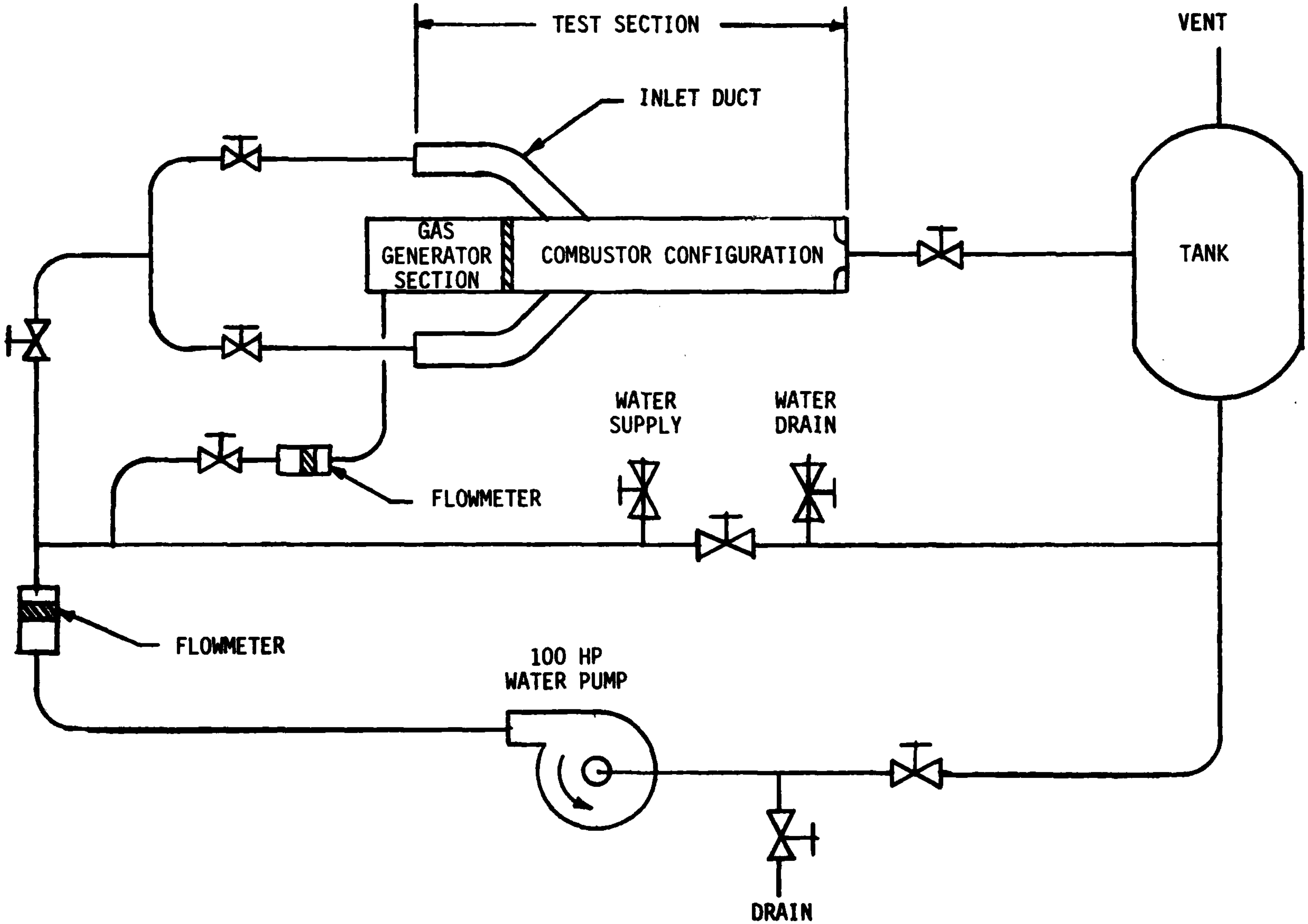


Figure 1. Schematic of Water Tunnel Test Rig Facility

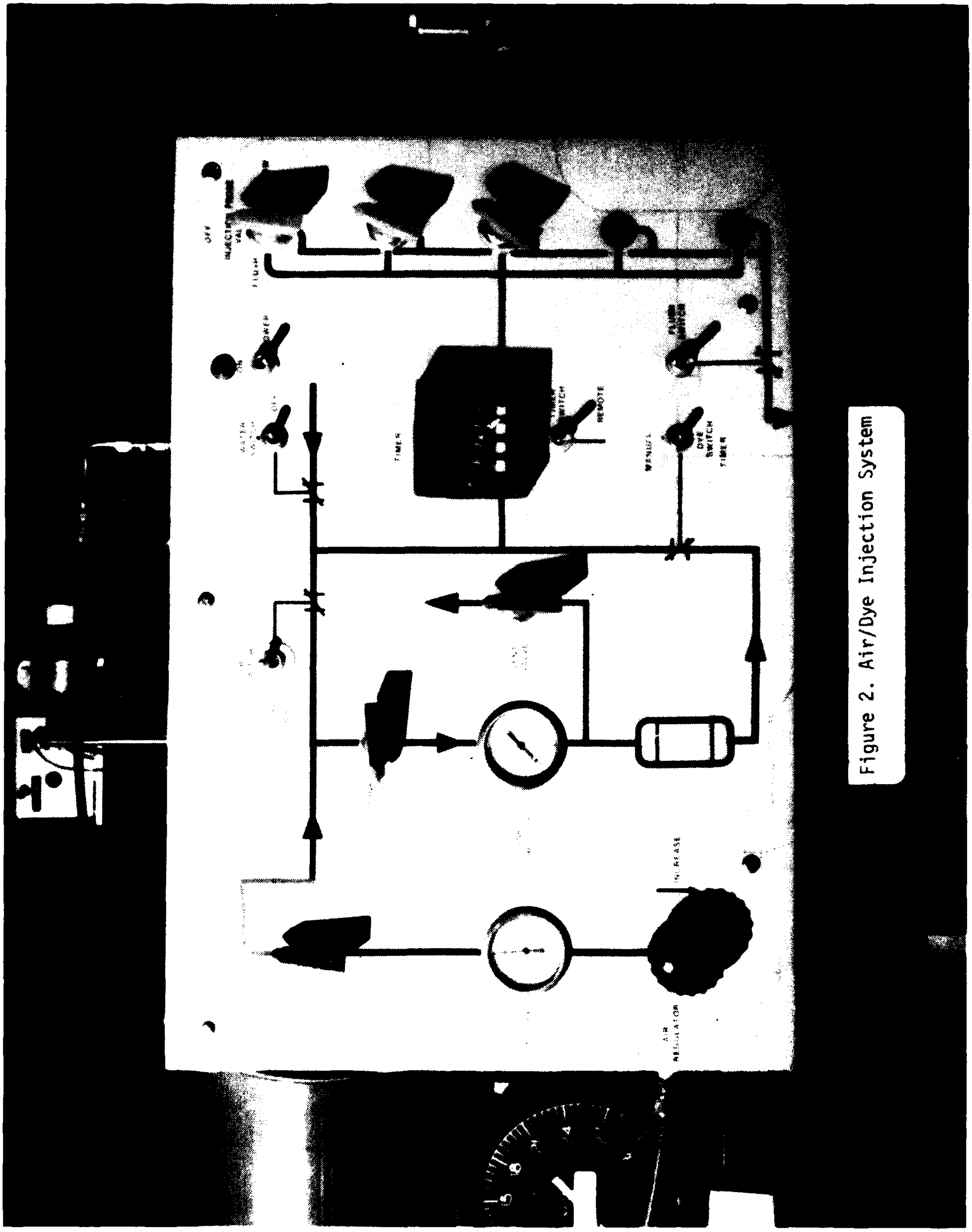


Figure 2. Air/Dye Injection System

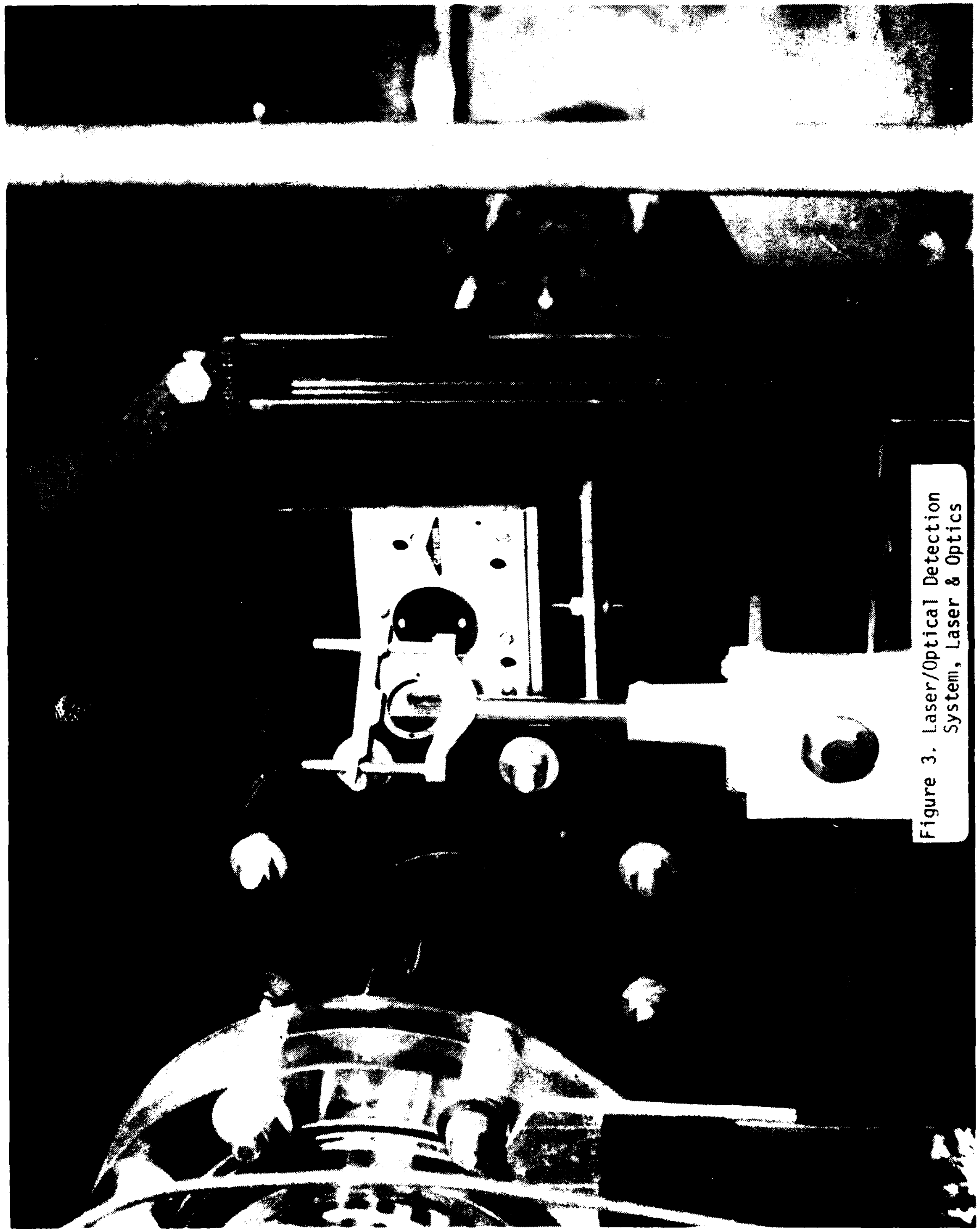


Figure 3. Laser/Optical Detection System, Laser & Optics

Figure 3. Cont'd, Photomultiplier Detector

utilized to detect and measure injected dye concentrations and time histories for residence time determinations.

The high intensity light source consists of a high voltage D.C. power supply, Figure 4, which powers a high intensity mercury lamp, Figure 5, for flow visualization purposes. The light source output is adjustable up to 65,000 lumens at 1000 volts D.C. The mercury lamp provides an intense source of radiant energy that is focused to a narrow plane beam. This light beam is used to observe internal flow patterns formed by injected air bubbles. The lamp housing is mounted onto a fixture above the combustor test section. The light beam from the lamp housing can be positioned perpenducular or parallel to the axis of the combustor and can be positioned at any point on the combustor axis.

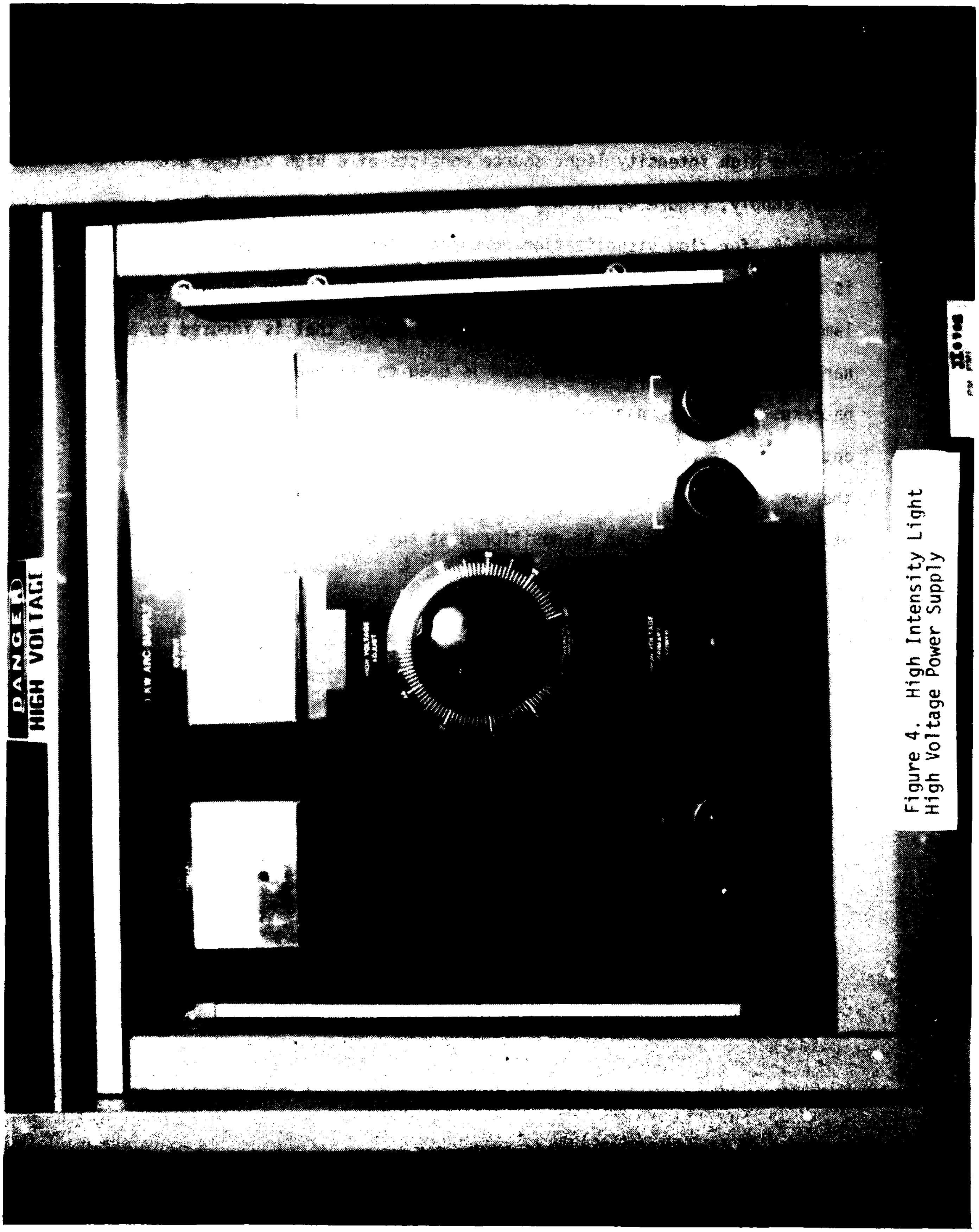


Figure 4. High Intensity Light
High Voltage Power Supply

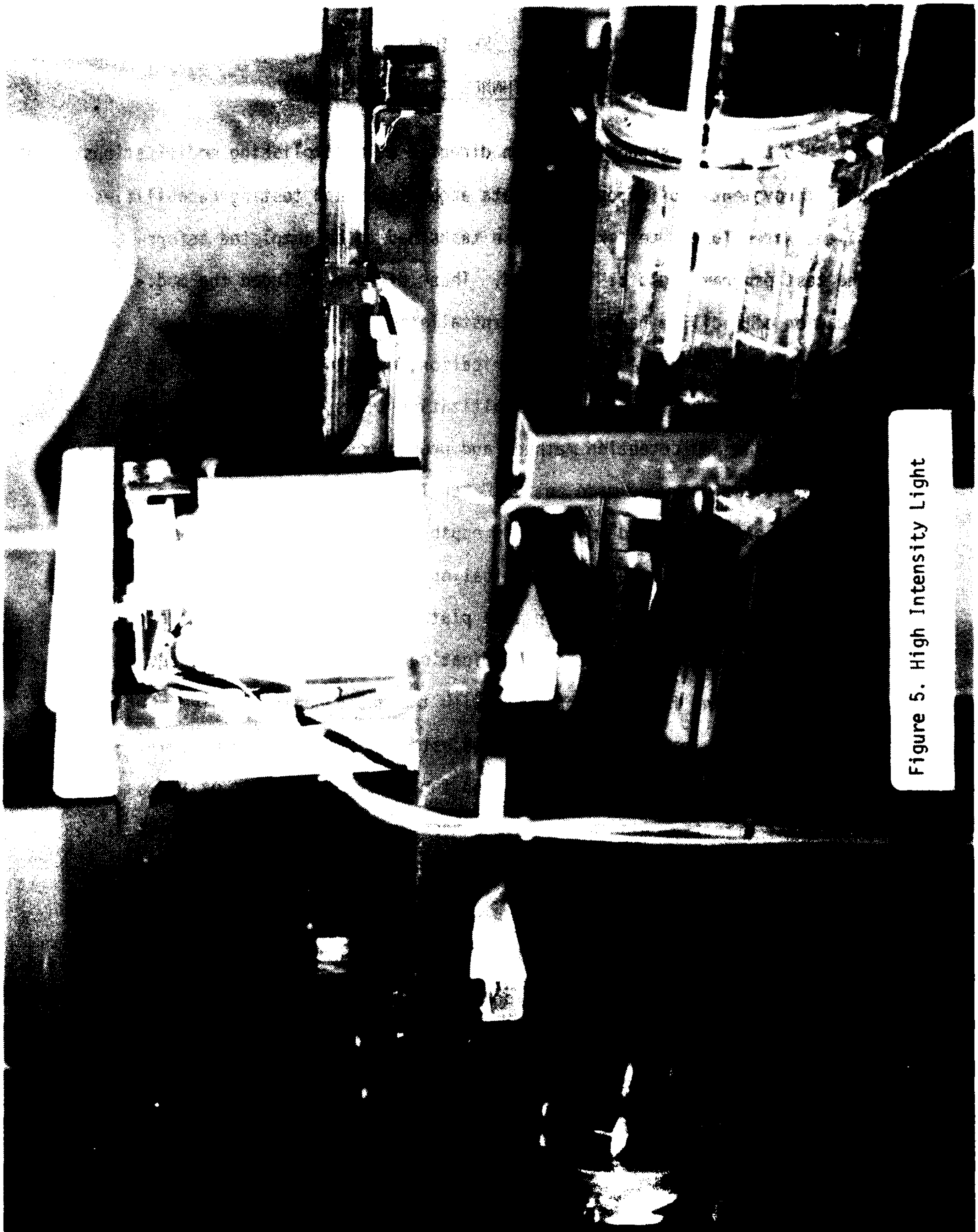


Figure 5. High Intensity Light

SECTION 3

WATER TUNNEL TEST RIG SUPPORT

UES technical support has been directed at accomplishing modifications and improvements to increase the data acquisition and testing capabilities of the Water Tunnel test rig. These tasks had to be completed before the test program could be initiated. These efforts included the modification of facility hardware; the installation and checkout of new instrumentation; the designing, fabrication, and testing of injection probes; the conducting of flow visualtization tests; and the testing of dye injection and detection methods and procedures.

Modifications were made on the Water Tunnel test rig to improve operation procedures and add testing capabilites. One of these improvements was a new gas generator modification which allows the injection of water flow through the combustor dome plate to simulate a gas generator flow. In conjunction with this modification, several new dome plates were designed and fabricated for use with the gas generator system. Another facility modification was an adjustable dome plate which could be repositioned during tunnel operation for quick observation of the dome plate effects. Also added to the test facility was a new support over the test section to allow mounting of the High Intensity Light Source and the Laser/optical system.

To increase the data acquisition capability of the Water Tunnel, several new items of instrumentation were installed and checked for proper operation. These items included new differential pressure transducers and gages for the measurement of various flow velocities, the

checkout and re-calibration of system water flowmeters, and the installation of a data acquisition system.

Air and dye injection probes were designed, fabricated, and tested in the Water Tunnel test rig to determine proper injection probe designs for specific purposes. Probes were designed to inject air or dye in long streams for observation of streamlines and also designed for quick dispersion of air or dye necessary for flow visualization and residence time measurements. Probes were also designed to inject air or dye in specific areas of the combustor configurations. Figure 6 shows some of the injection probes designed and tested.

As improvements were accomplished and the test procedures examined, various flow visualization techniques were tested to obtain combustor flow information. Initial flow visualiation consisted of drawings made of combustor flows for different test parameters by utilizing air bubble injection. Subsequently photographs and high speed motion pictureswere taken of both air and dye injections to obtain combustor flow field patterns and information on dye injection procedures. The visualization data obtained provided an understanding of the combustor vortex formations, streamline patterns, and the effects of configuration changes.

In preparation of the conducting of the residence time tests reported herein, numerous dye detection, injection, and calibration tests were performed. The laser/optical and photomultiplier detector system was setup and adjusted through the combustor configuration. Dye detection, within the test configuration, was from a point on the left inlet duct, when viewing the nozzle end of combustor, approximately 2.0 inches from the combustor wall to a point 6.0 inches pass the combustor exit nozzle

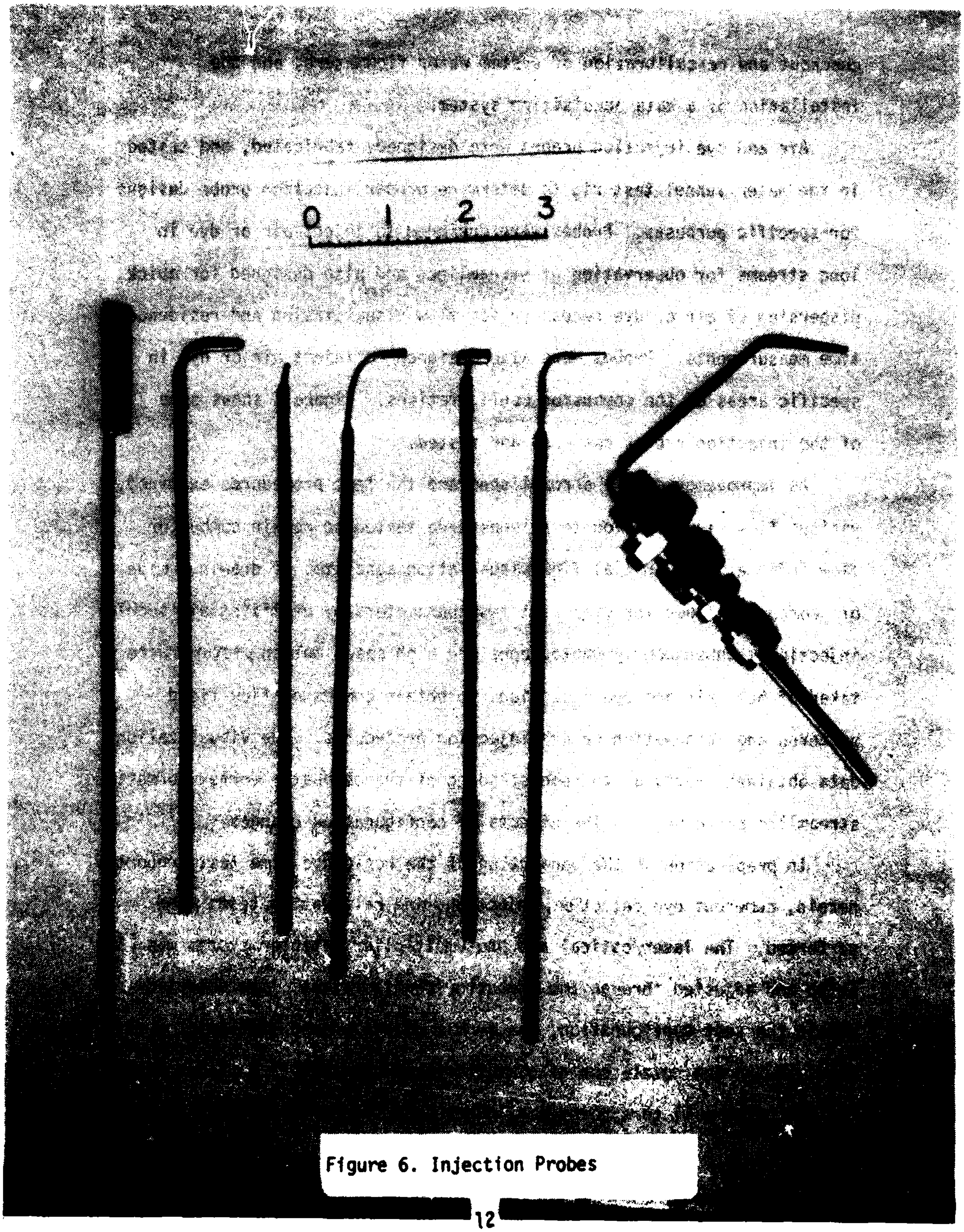


Figure 6. Injection Probes

face. The laser detector output signals were recorded directly onto a Honeywell 1858 Visicorder oscillograph. Calibrations of the photomultiplier detectors were accomplished by injecting known quantities of dye into the closed Water Tunnel system, while in operation, and recording the detector outputs for each known dye concentration. This formation allowed the formulation of dye calibration curves as shown in Figure 7. Therefore, knowing the volume flowrate and detector outputs the quanity of injected dye could be determined. Obtaining this information for the inlet and exit points of the combustor determined the residence time of the dye within the configuration.

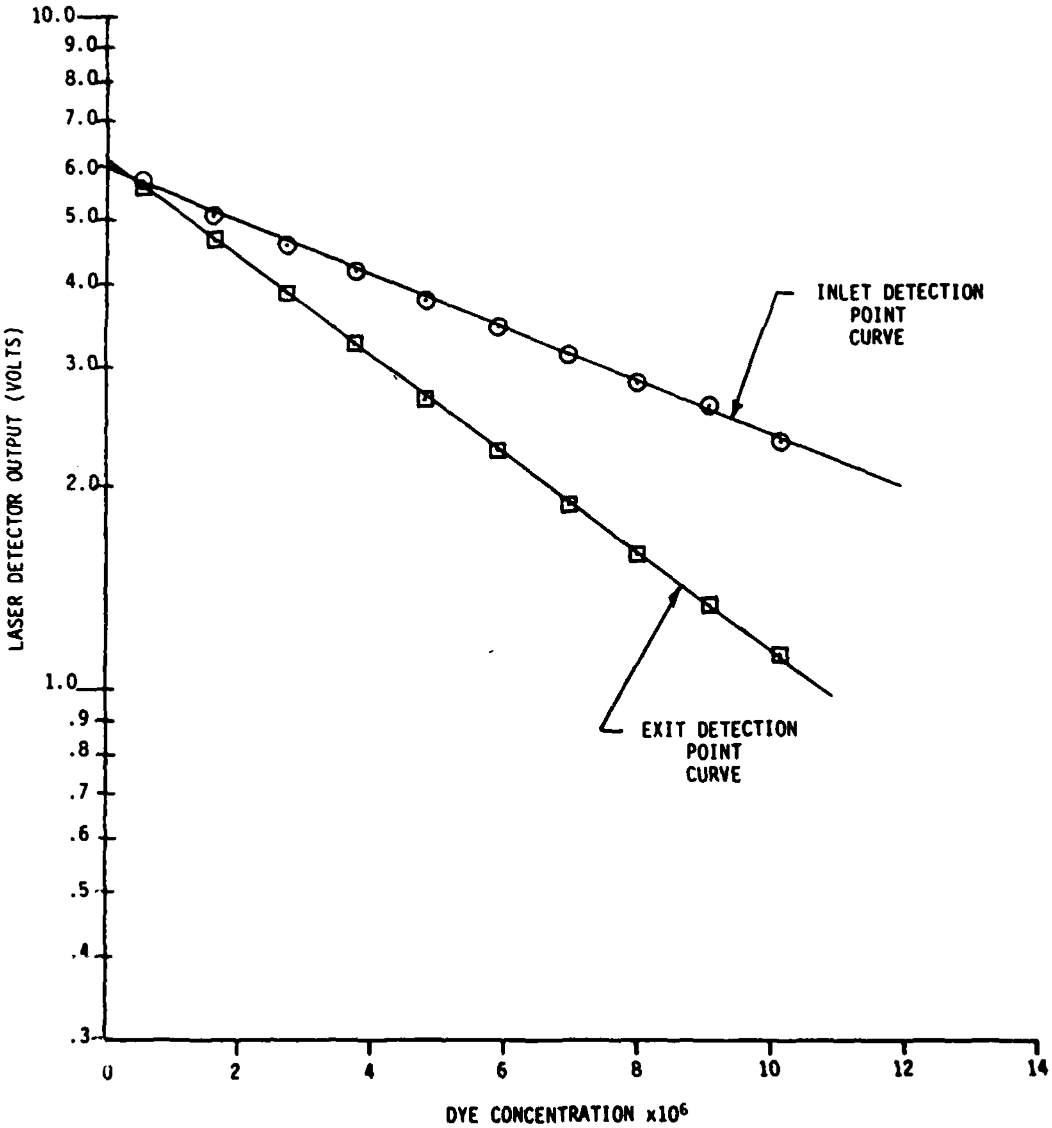


Figure 7. Dye Calibration Curves

SECTION 4

TECHNICAL SUPPORT OF OTHER TEST RIGS AND FACILTIIES

During this reporting period, UES has also provided technical support to the Burner Thrust Stand test rig and to the Cold Flow Channel.

4.1 Burner Thrust Stand Test Rig Support

UES has supported the Burner Thrust Stand, Room 18, Bldg. 18, to improve the capabilities of the facility. UES designed, purchased, and installed a WWVB time code and video insertion system. This WWVB time code system receives and displays a National Bureau of Standards time signal that provides a time reference for all video and computer data generated at the Burner Thrust Stand faciltiy.

4.2 Cold Flow Channel Support

UES has provided technical personnel and support to the Cold Flow Channel, Bldg. 450, to conduct research studies of gas mixing and gas flows associated with ramjet combustor configurations. Support has involved the operation and maintenance of the Ion Mass Spectrometer and related systems utilized in gas sampling experimentation and the setup and operation of the Cold Flow Channel.

Several facility modification have been completed to improve the operation and capabilities of the Cold Flow Channel. The major modification performed was the design, fabrication, and installation of a new Cold Flow Channel control panel. This new control panel replaces the remote control panel and provides for more efficient operation of the facility.

SECTION 5

MULTI-DUCTED INLET COMBUSTOR CONFIGURATION

The test model configuration is the most recent dump combustor design to be investigated by the Ramjet Technology Branch AFWAL/PORT. The multi-ducted inlet combustor configuration is made up of two rectangular inlet ducts, a combustor, and a gas generator section. The test model configuration physical dimensions and components are detailed in Figure 8. A photograph of the test configuration is shown in Figure 9.

The two rectangular inlet ducts curve to intersect the combustor at inlet angles of 30, 45 or 60 degrees. The test data presented in this interim report are for an inlet angle of 45 degrees. The centerline of both inlet ducts intersect the combustor at the same axial station and are located radially at 90 degrees to each other. The internal dimensions of the inlet ducts are 2.0 inches by 2.75 inches. The upstream edge of the inlet ducts is taken as the combustor longitudinal zero reference point. Longitudinal measurements downstream of the zero reference point are positive and are negative upstream of the zero reference point, refer to Figure 8.

The combustor is a cylinder with a 6.0 inch I.D. and measures 39.0 inches in length from the combustor longitudinal zero reference point to the exit nozzle. The combustor dome plate is located at the upstream end of the combustor and can be positioned axially from the zero reference point to approximately 10.0 inches forward of the inlet ducts. The configuration of the dome plate can be modified to simulate gas generator operation or to test fuel injection methods. Test results reported herein are for a flat dome plate with no gas generator fluid flow.

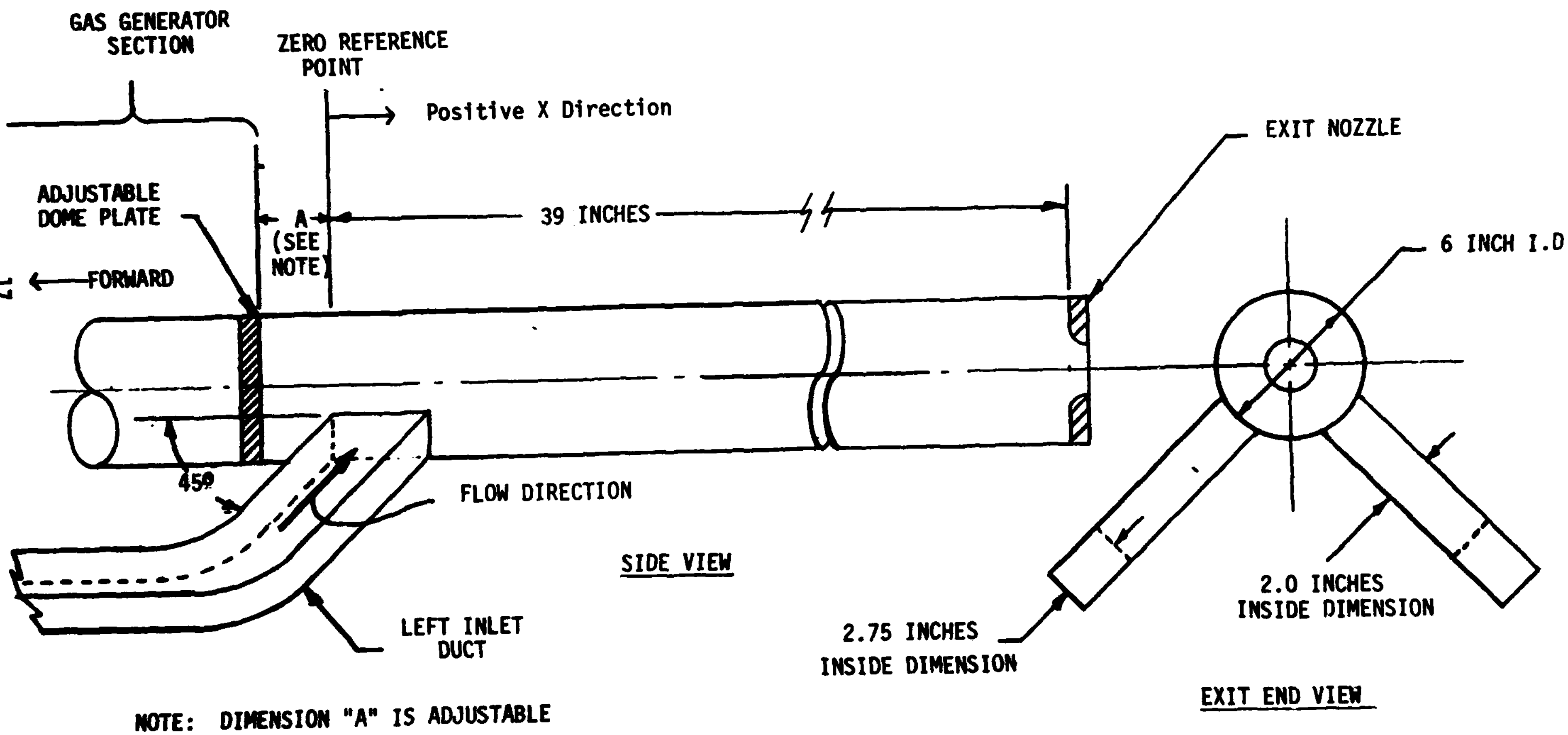


Figure 8. Multi-Ducted Inlet Combustor Configuration

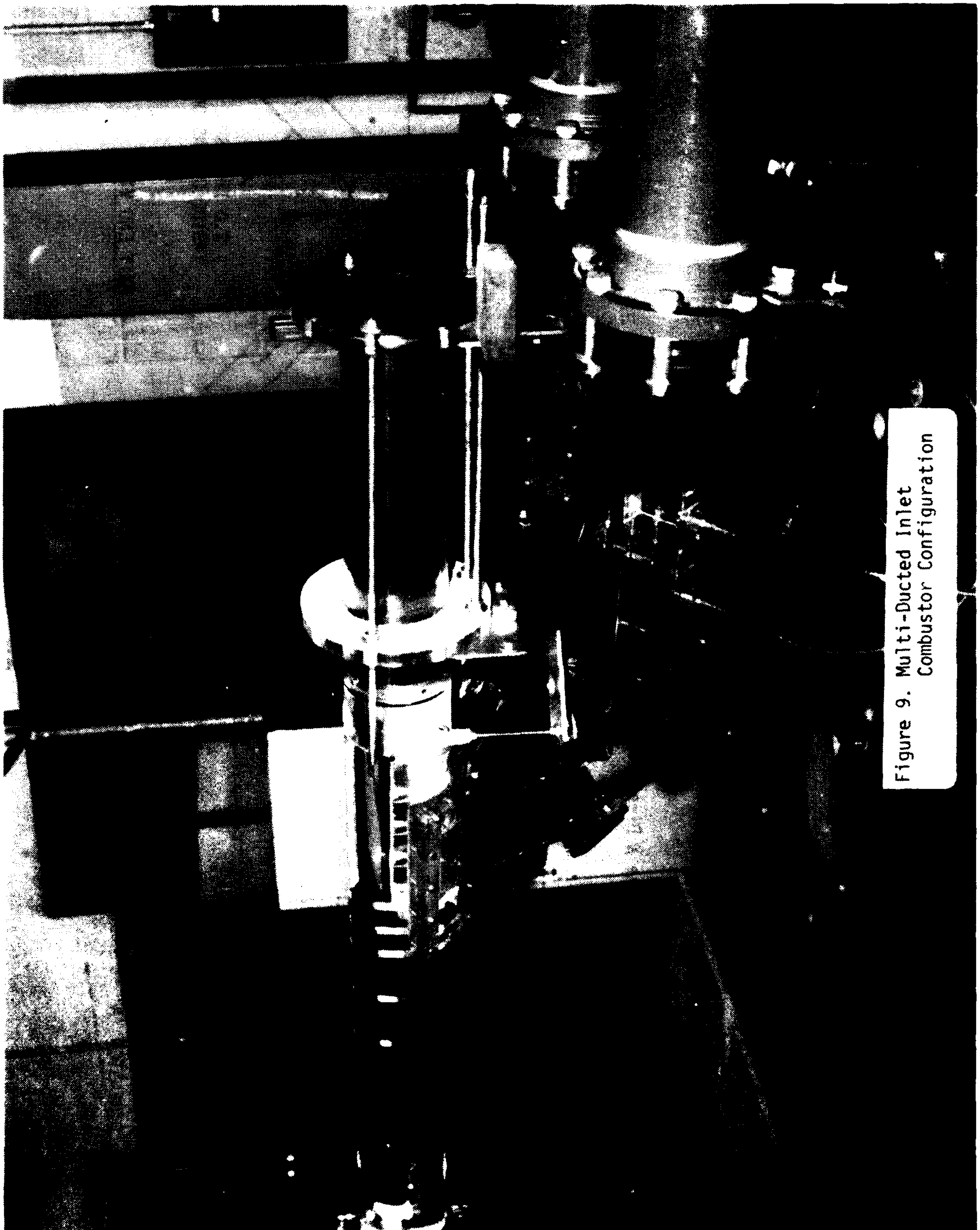


Figure 9. Multi-Ducted Inlet
Combustor Configuration

The exit nozzle of the combustor is replaceable to allow for different exit area to combustor area ratios to be tested. Area ratios of 0.450, 0.552, and 0.637 are available. An area ratio of 0.552 was used while conducting the tests reported on in this report.

The gas generator section of the mult-ducted inlet configuration is designed to simulate gas generator operation or fuel injection. Water flow can be injected through specially designed dome plates and can be regulated in proportion to the total tunnel flow. Injection of fluid through the dome plate was not utilized for testing during this reporting period but will be investigated as the program progresses. The gas generator section is also designed to allow visual and photographic observation of the internal flow patterns during Water Tunnel operations.

SECTION 6

INSTRUMENTATION

The initial instrumentation capability of the Water Tunnel test rig facility was considered inadequate for the obtaining of quantitative and qualitative data on flow characteristics of multi-ducted inlet combustors. Therefore, the initial tasks performed by UES, during this report period, were to upgrade the data monitoring, data acquisition, and analysis capabilities of the facility. To accomplish this task several new items of instrumentation and test equipment were purchased and installed in the Water Tunnel test rig facility. Included in these items were a Mod Comp MODAS III Computer System, a Honeywell 1858 Visicorder Oscillograph, a Lafayette Data Analyzer Projector, an ATC Digital Timer, a D.C. Power Supply, Sens-o-metrics Differential Pressure Transducers, and a Data Precision Digital Multimeter. Most of these items are now incorporated into a new data acquisition system. A schematic of the Water Tunnel data acquisition system is shown in Figure 10.

In addition to the purchasing of new equipment, UES personnel have fabricated specialized test equipment for use in the conducting of residence time studies. A new air/dye injection control panel, Figure 2, was fabricated which allows precise and controlled injection of air bubbles and/or dye into the test model. Also fabricated were two photomultiplier detections units, Figure 3, that are capable of providing detailed information of flow characteristics through the detection of injected dye. Additional facilty instrumentation improvements will be accomplished as requirements arise to perform the required test program.

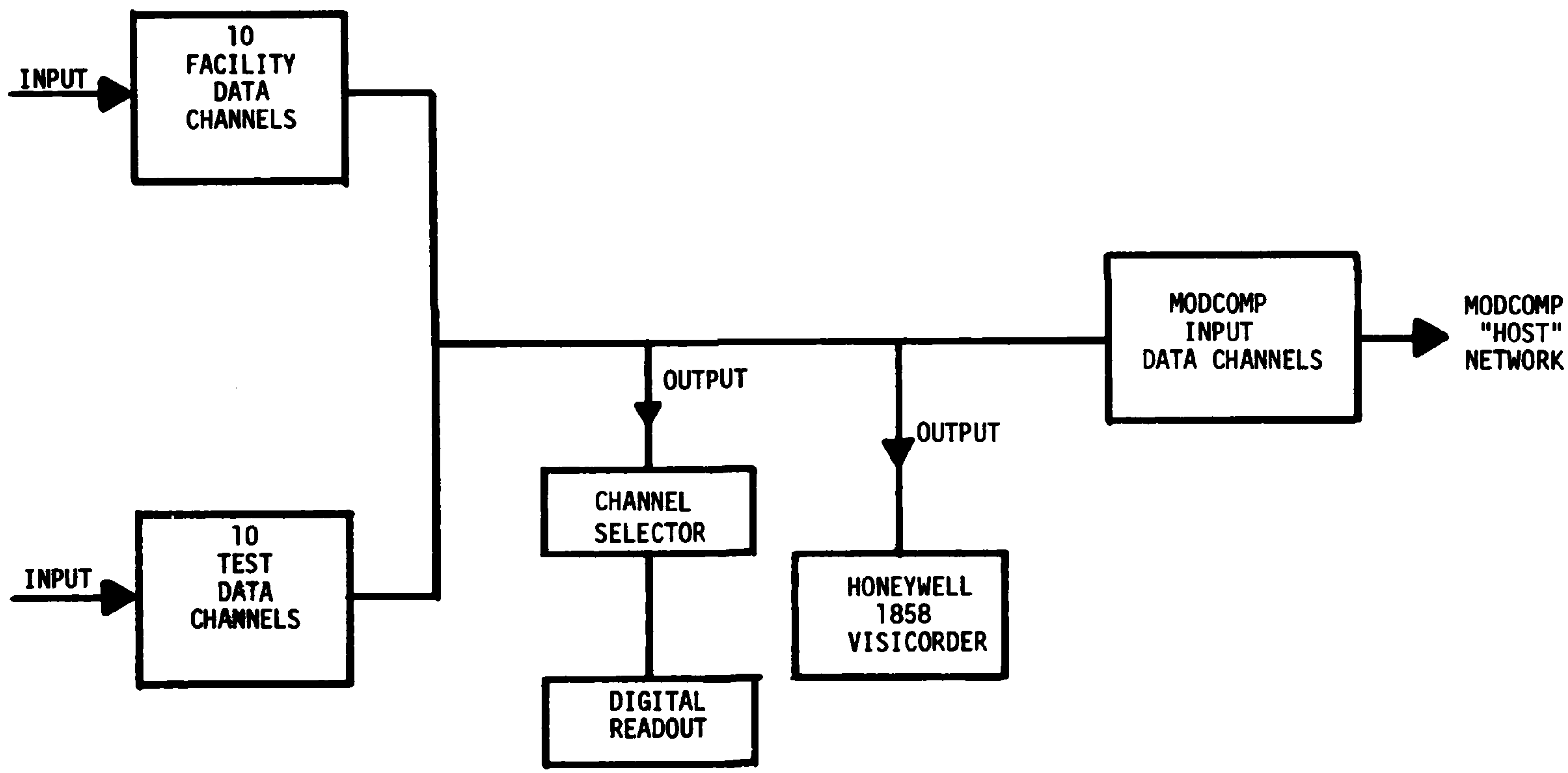


Figure 10. Schematic of Data Acquisition System

SECTION 7

TEST PROGRAM

The test program to obtain residence time data of the multi-ducted 45 degree inlet angle combustor configuration involved the varying of two test parameters, total fluid flow rate and combustor dome plate position. Test runs were conducted at inlet duct flow velocites of 4.37 feet per second (150 GPM) to 14.58 feet per second (500 GPM) in increments of 1.46 feet per second (50 GPM) for each of nine solid dome plate positions. Water flow velocity was balanced between the two inlet ducts. Combustor dome plate positions tested were 0, -1, -2, -3, -4, -5, -6, -7, and -8 inches from the zero reference point. The water temperatures for all test runs were between 85 and 105 degrees Fahrenheit.

For each test run shown in Table 1 the water flow was allowed to stabilize and then a small quantity of dye, 0.01 to 0.03 milliliters, was injected upstream of the detection point. The injected dye dispersed into the inlet duct fluid and then entered the combustor and dome plate region. The dyed fluid then passed out the combustor exit nozzle and passed the exit detection point. During the traverse of the dyed fluid through the combustor an oscillograph trace was obtained of the two laser detector outputs. An example of a typical detector output time history trace is shown in Figure 11. This data was then analyzed to obtain dye concentration and quantity versus time information, Figure 12, from which residence time determinations were made.

Table 1. Residence Time Test Run Schedule

FLOW RATE GPM	150	200	250	300	350	400	450	500
DOME PLATE POSITION (in.)								
0.0	71282-9	71282-10	71282-11	71282-12	71282-13	71282-14	71282-15	71282-16
-1.0	71382-1	71382-2	71382-3	71382-4	71382-5	71382-6	71382-7	71382-8
-2.0	71282-1	71282-2	71282-3	71282-4	71282-5	71282-6	71282-7	71282-8
-3.0	71382-9	71382-10	71382-11	71382-12	71382-13	71382-14	71382-15	71382-16
-4.0	71482-1	71482-2	71482-3	71482-4	71482-5	71482-6	71482-7	71482-8
-5.0	71582-1	71582-2	71582-3	71582-4	71582-5	71582-6	71582-7	71582-8
-6.0	71582-9	71582-10	71582-11	71582-12	71582-13	71582-14	71582-15	71582-16
-7.0	71682-1	71682-2	71682-3	71682-4	71682-5	71682-6	71682-7	71682-8
-8.0	71682-9	71682-10	71682-11	71682-12	71682-13	71682-14	71682-15	71682-16

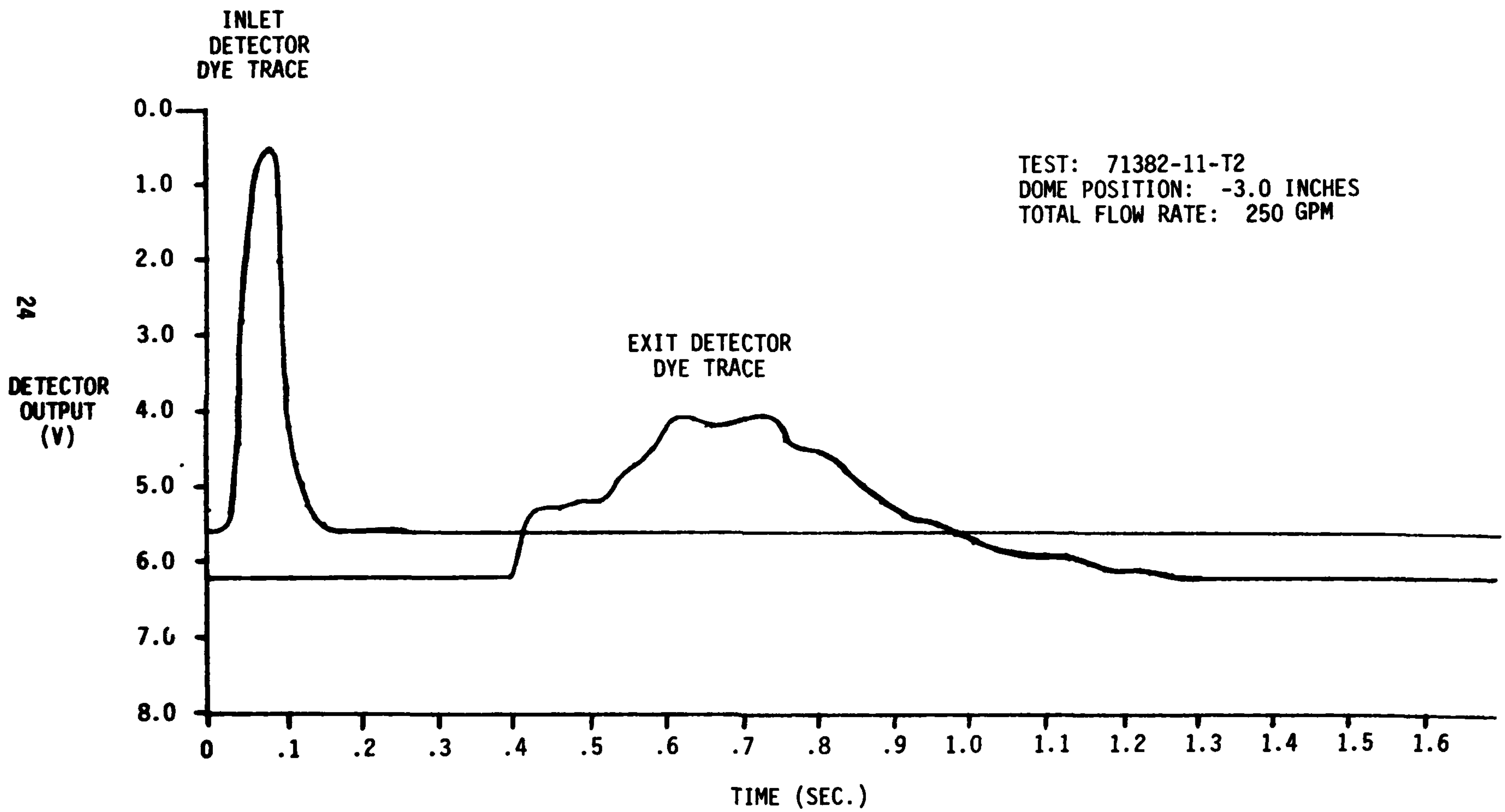


Figure 11. Example of a Time History of Laser Detector Outputs for Dve Injection Test

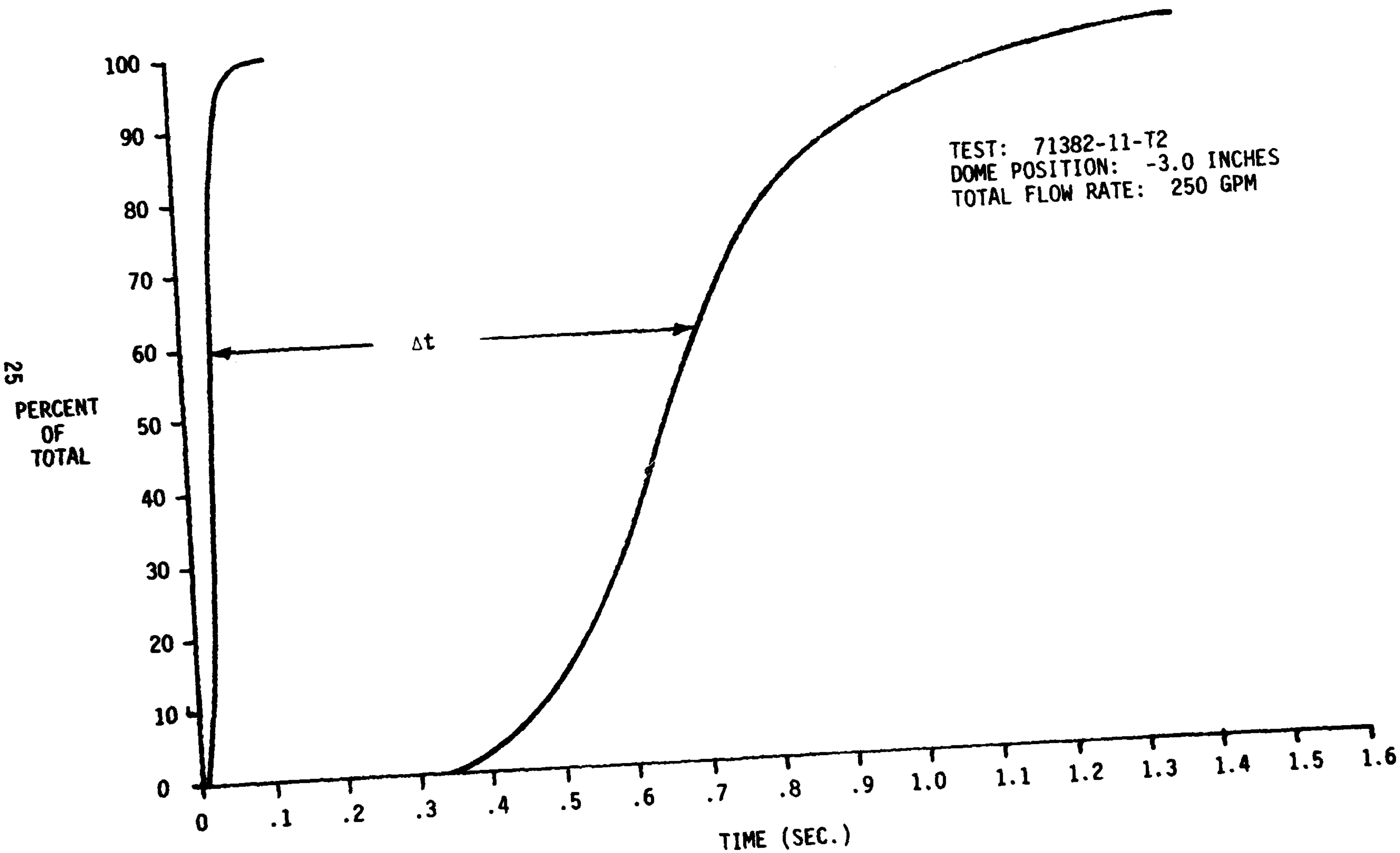


Figure 12. Example of Dye Quanity Versus Time Curve for Dye Injection Test

SECTION 8

DATA REDUCTION

8.1 Dye Calibrations

Dye calibrations were required so that dye concentrations and quantities could be accurately determined. The dye utilized for test purposes was Pontamine Fast Orange W Liquid manufacured by the Mobay Chemical Corporation. This industrial Dye was selected for its light absorption characteristics in the wavelength range (415 nm) of the Argon laser used for detection purposes. As the dye to water concentration increases at the laser detection points in the Water Tunnel, the photomultiplier detector outputs decrease.

The detector output versus dye concentration curve, Figure 7, was obtained by injecting known quanitites of dye into the closed Water Tunnel system and allowing it to disperse completely while the tunnel was operating. After the dye and water had completely mixed, the voltage outputs of the two photomultiplier detectors were recorded. This procedure was continued until the detector outputs were reduced to approximately one tenth of their initial voltage outputs. The data was then plotted and curve fitted to obtain the dye concentration equations used for data reduction.

Dye Calibration Equations:

Inlet Detector - $C_i = -1.091 \times 10^{-5} \ln \frac{V_{Di}}{V_{oi}}$

Exit Detector - $C_e = -5.972 \times 10^{-6} \ln \frac{V_{De}}{V_{oe}}$

8.2 Dye Integration Procedure

Using the photomultiplier detector output data from the oscillograph traces, Figure 11, and the test conditions of each test run, the quantity of dye passing each detection point was determined. Then the percent of total dye quantity was plotted versus time for both the inlet and the exit detection points to obtain the curves shown in Figure 12.

Integration and Summation Equations:

$$Q_i = C_i \times Vol_i$$

$$Q_e = C_e \times Vol_e$$

$$Q_{Ti} = \sum_{j=1}^{n} Q_{ij}$$

$$Q_{Te} = \sum_{J=1}^{n} Q_{ej}$$

Percent of Total at Inlet $= \dfrac{Q_{ij}}{Q_{Ti}}$; $j = 1$ to n

Percent of Total at Exit $= \dfrac{Q_{ej}}{Q_{Te}}$; $j = 1$ to n

8.3 Resident Time Determination

The one dimensional residence time as defined in Ref. 8 is equal to the ratio of the total volume of the fluid within the combustor chamber divided by the total volume flow rate entering the combustor.

$$t_r = \frac{\text{Combustor Volume}}{\text{Total Volume Flow Rate}}$$

The one dimensional residence times were used as the base line for comparision with the residence times obtained from the dye injection tests. Table 2 gives these one dimensional residence times for the test configurations and inlet flow conditions.

Table 2. One-Dimensional Residence Time

FLOW RATE GPM	RESIDENCE TIMES (SEC.) 150	200	250	300	350	400	450	500
DOME PLATE POSITION (in.)								
0.0	2.021	1.516	1.213	1.010	0.866	0.758	0.674	0.606
-1.0	2.070	1.552	1.242	1.035	0.887	0.776	0.690	0.621
-2.0	2.119	1.589	1.271	1.059	0.908	0.794	0.706	0.636
-3.0	2.168	1.626	1.301	1.084	0.929	0.813	0.723	0.650
-4.0	2.217	1.663	1.330	1.108	0.950	0.831	0.739	0.665
-5.0	2.266	1.699	1.359	1.133	0.971	0.850	0.755	0.680
-6.0	2.315	1.736	1.389	1.157	0.992	0.868	0.772	0.694
-7.0	2.364	1.773	1.418	1.182	1.013	0.886	0.788	0.709
-8.0	2.413	1.809	1.448	1.206	1.034	0.905	0.804	0.724

The multi-ducted inlet combustor residence times, from the dye injection test data, were determined by taking the average of the time deltas between the inlet and exit percent of total dye quanity data for equal dye quantities. This time delta measurement is shown on Figure 12 one of the dye quanity versus time curves.

SECTION 9

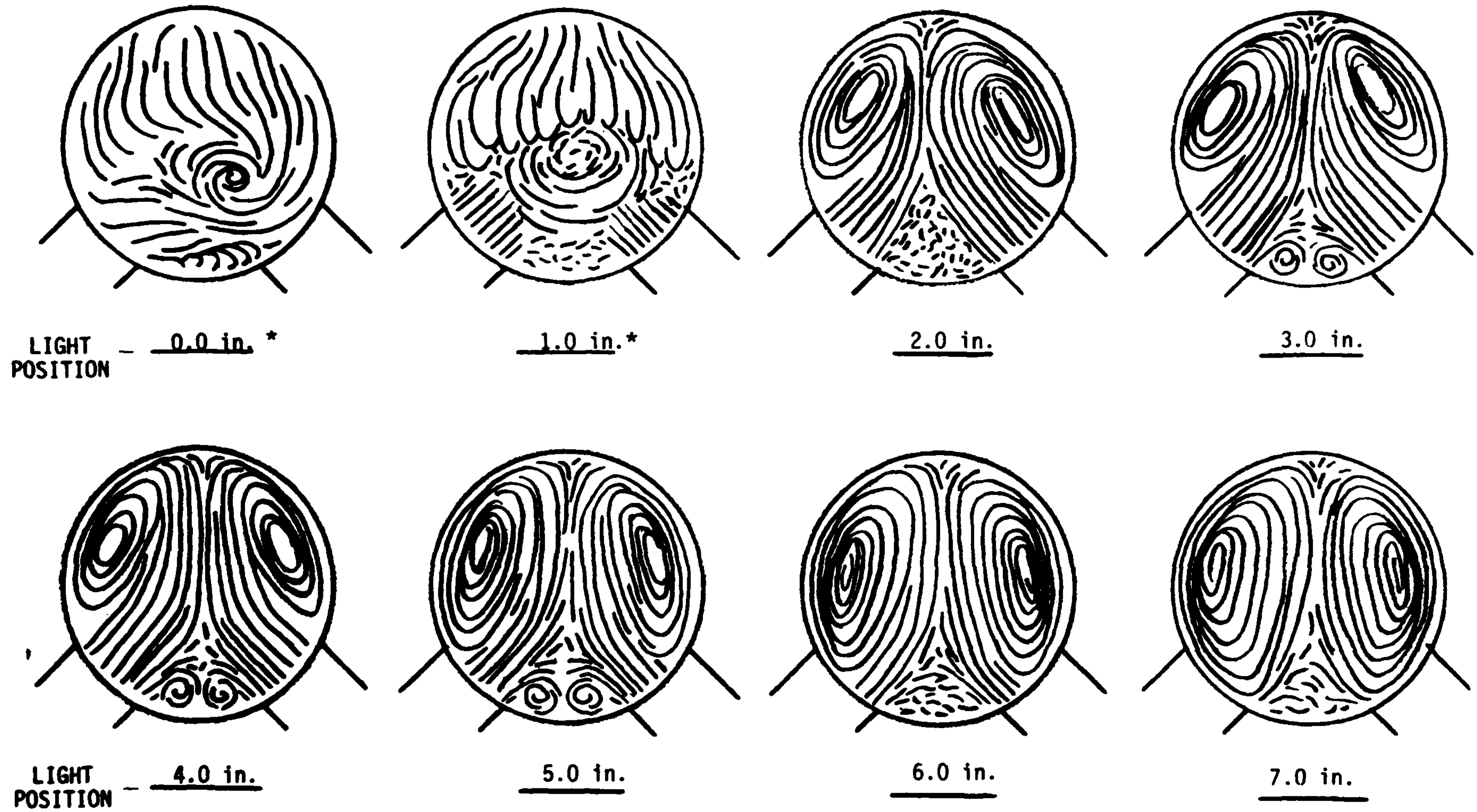
DATA PRESENTATION

Test data presented in this Interim Report represents initial test information and preliminary residence time data obtained in performing research and development of the multi-ducted inlet combustor configuration. Data reported herein consists of drawings and photographs showing combustor flow field patterns for different combustor configurations and residence time data for the 45 degree dual inlet duct combustor.

Figures 13-16 show drawings of combustor flow field patterns at various axial locations for dome plate positions of 0.0, -2.0, -4.0 and -6.0 inches respectively. All drawings were obtained using the High Intensity Light and air bubble injection. Water flow was balanced in inlet ducts at a constant flow velocity of 8.75 feet per second (300 GPM). Figures 17-21 are photographs of flow field patterns at combustor axial stations of -2.0, 0.0, +2.0, +4.0 and +8.0 inches respectively, with the dome plate located at -2.0 inches. Inlet flow velocity was 8.75 feet per second (300 GPM).

Presented in Figures 22-30 are the plots of 1-D residence times and dye injection residence times plotted versus the inlet duct flow Reynolds number per foot. Each plot is for a different combustor dome plate position. Table 3 presents a tabulation of these calculated residence times using the dye injection method. Figure 31 shows the variation of measured residence times versus combustor dome plate positions for the total tunnel flow rates tested. Figures 32-34 are plots of measured residence times versus total tunnel flow rates for different dome plate positions. Table 4 gives the values of the inlet duct flow velocities and Reynolds number per foot for each tunnel total flow rate condition.

COMBUSTOR DOME PLATE LOCATION: 0.0 in.
INLET CONFIGURATION : 45 DEGREES
FLOW CONDITIONS : 300 GPM (BALANCED)



* - FLOW DIRECTION OBSERVED IN BOTH CLOCKWISE AND COUNTER CLOCKWISE DIRECTIONS.

Figure 13. Drawings of Combustor Flow Patterns, DP = 0.0 in.

COMBUSTOR DOME PLATE LOCATION: 0.0 in.
INLET CONFIGURATION : 45 DEGREES
FLOW CONDITIONS : 300 GPM (BALANCED)

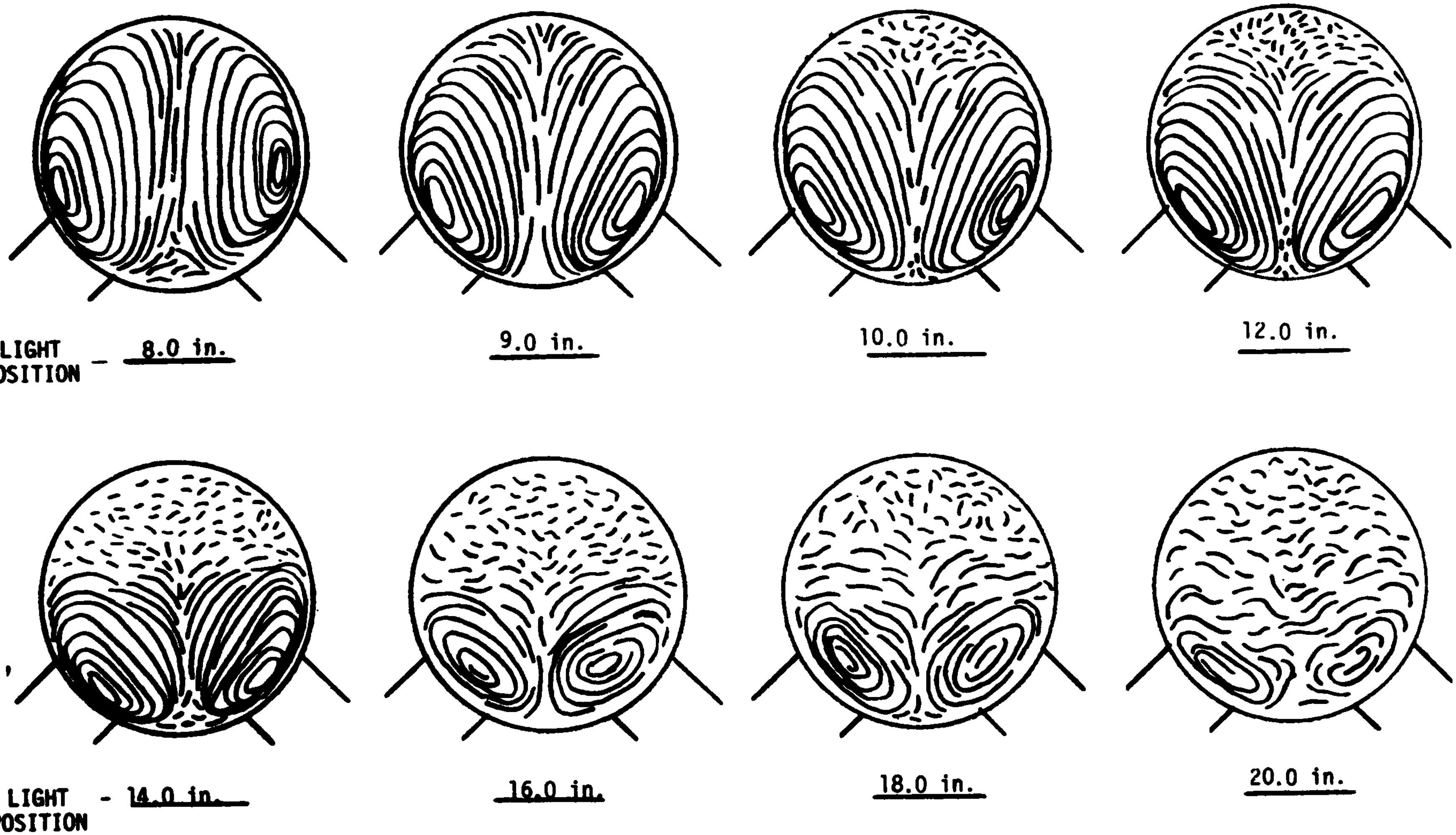


Figure 13. Cont'd.

COMBUSTOR DOME PLATE LOCATION: -2.0 in.
INLET CONFIGURATION : 45 DEGREES
FLOW CONDITIONS : 300 GPM (BALANCED)

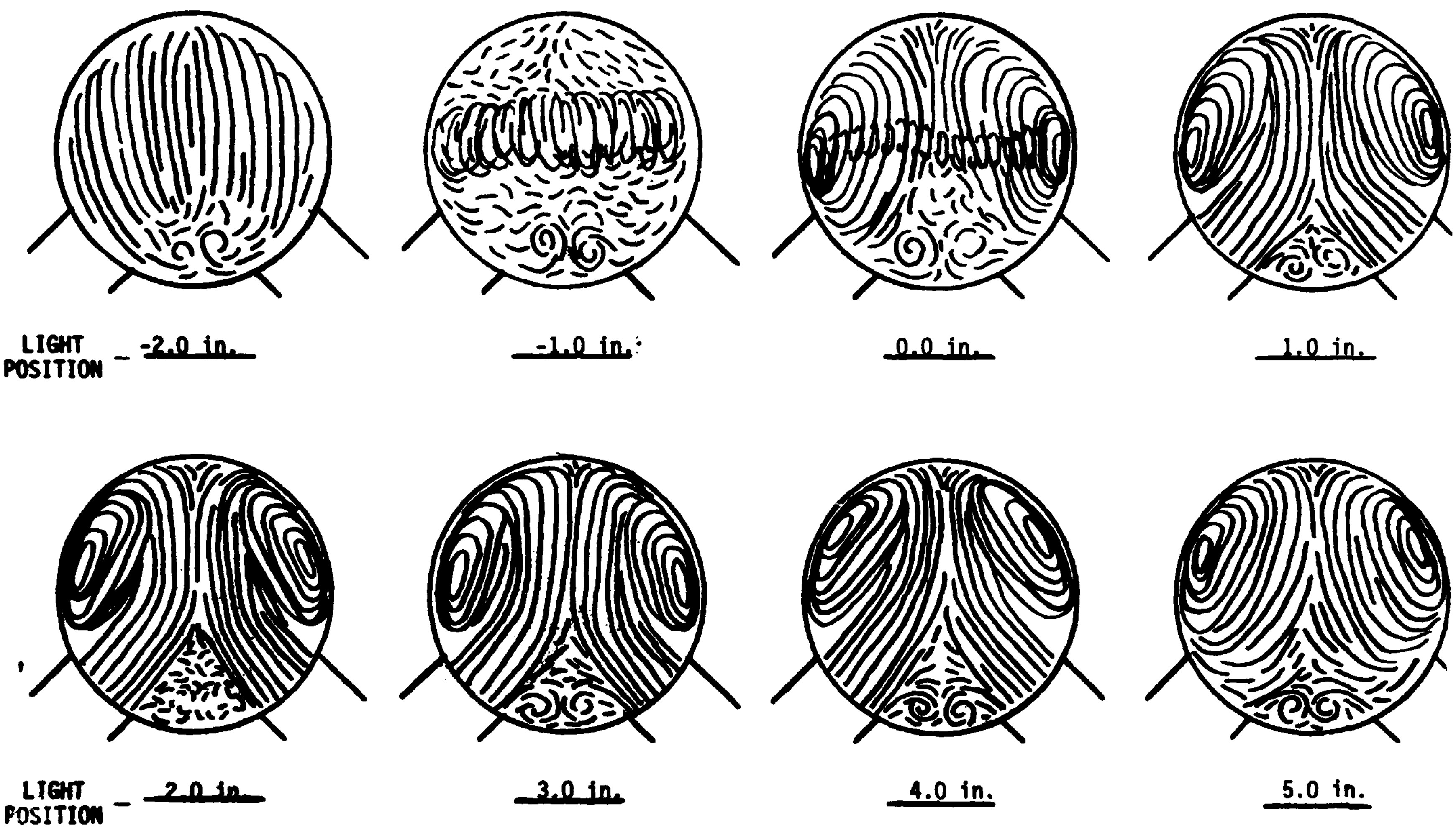


Figure 14. Drawings of Combustor Flow Patterns, DP = -2.0 in.

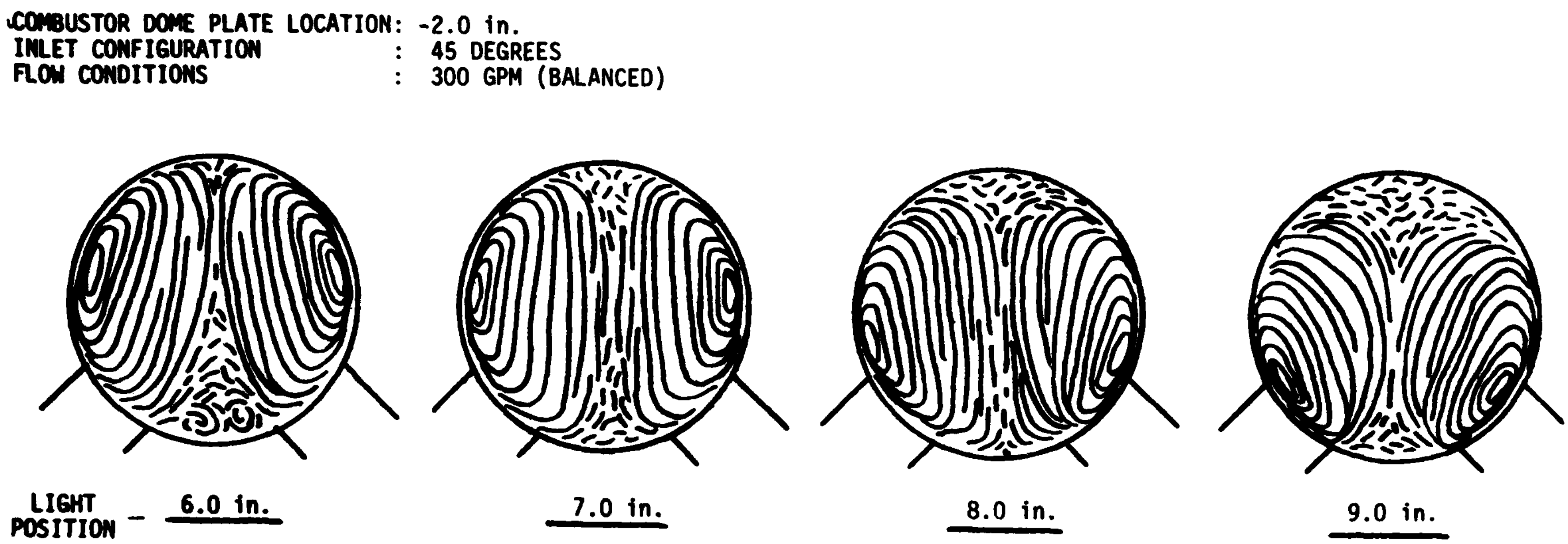
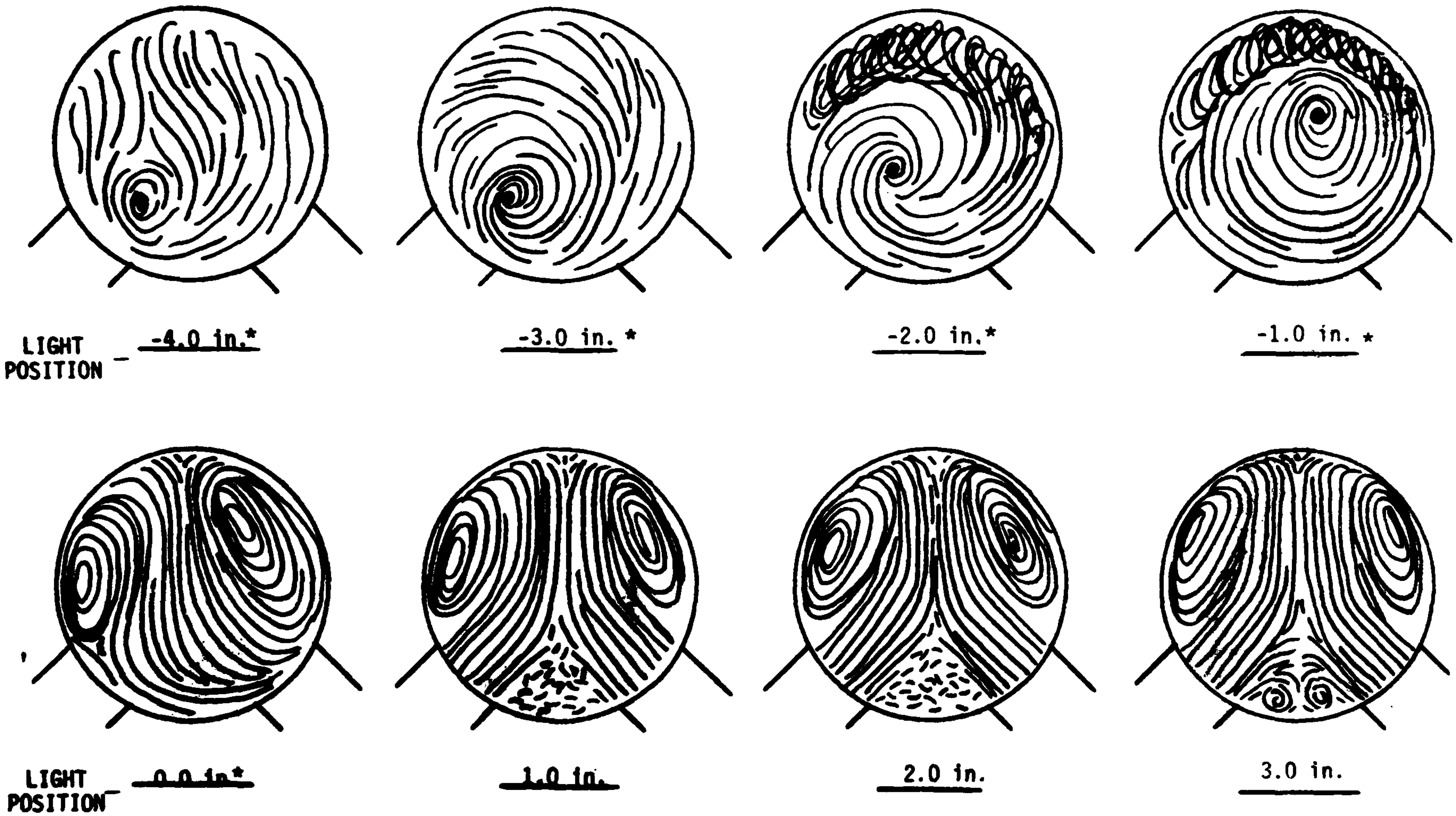


Figure 14. Cont'd.

COMBUSTOR DOME PLATE LOCATION: -4.0 in.
INLET CONFIGURATION : 45 DEGREES
FLOW CONDITIONS : 300 GPM (BALANCED)



* - FLOW DIRECTION OBSERVED IN BOTH CLOCKWISE AND COUNTER CLOCKWISE DIRECTIONS.

Figure 15. Drawings of Combustor Flow Patterns, DP = -4.0 in.

COMBUSTOR DOME PLATE LOCATION: -4.0 in.
INLET CONFIGURATION : 45 DEGREES
FLOW CONDITIONS : 300 GPM (BALANCED)

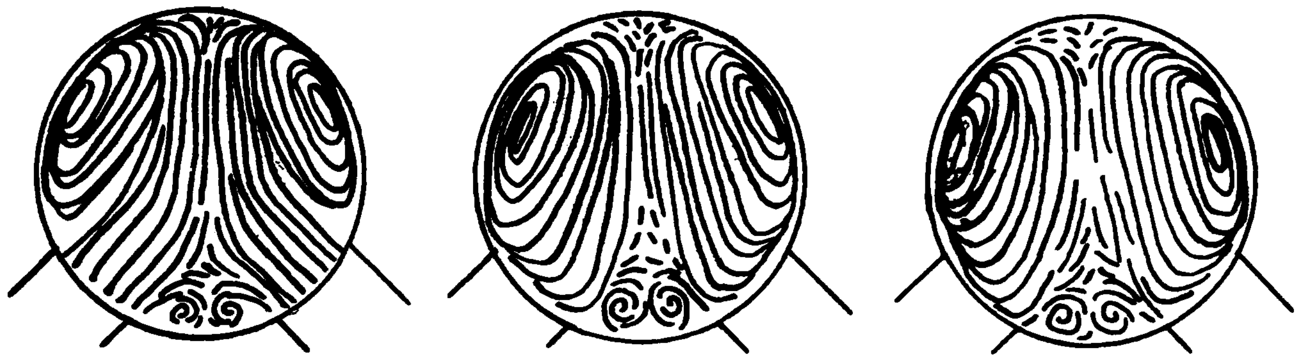
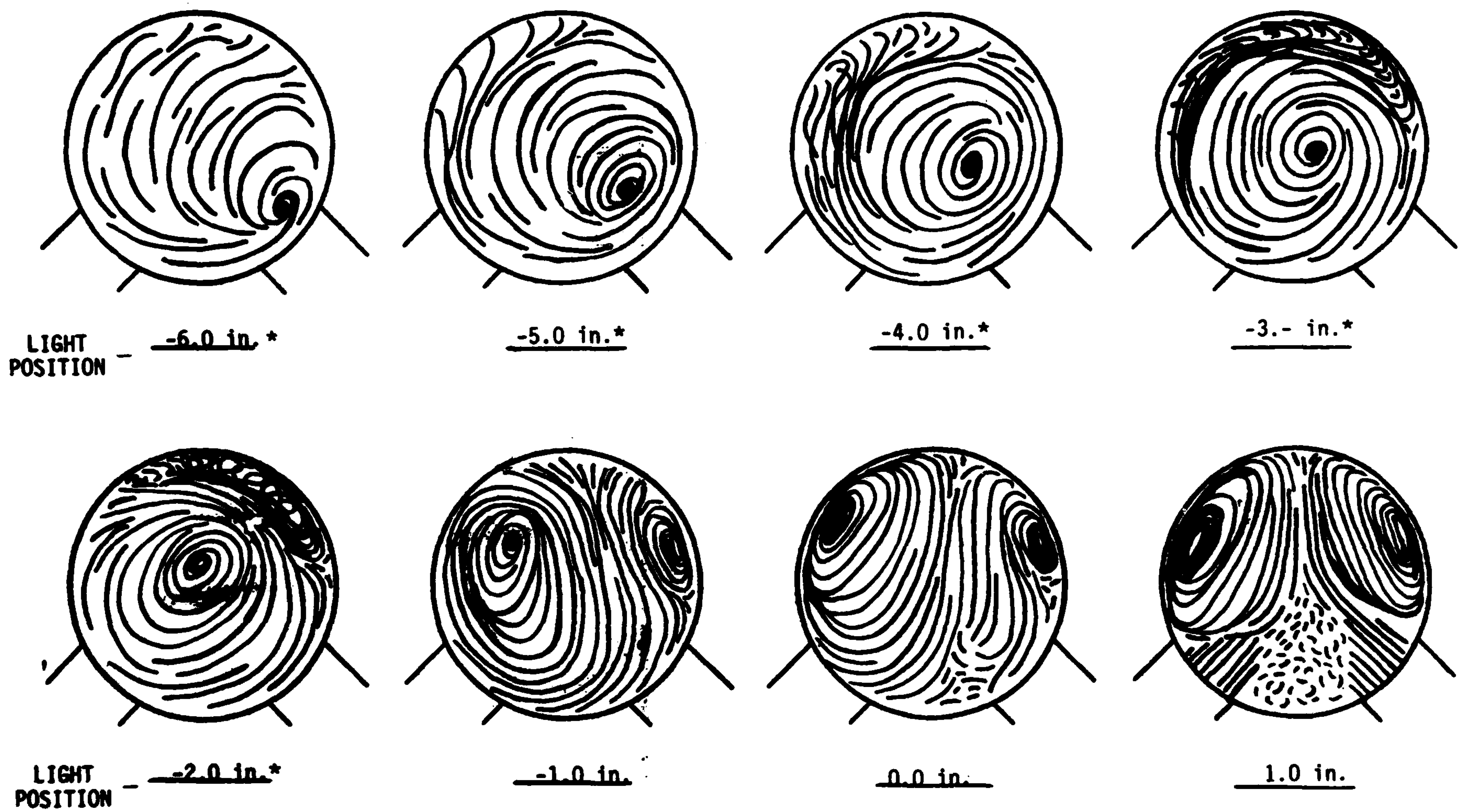


Figure 15. Cont'd.

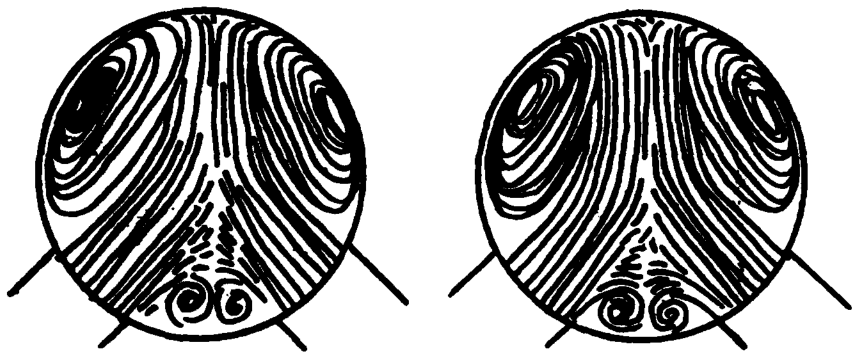
COMBUSTOR DOME PLATE LOCATION: -6.0 in.
INLET CONFIGURATION : 45 DEGREES
FLOW CONDITIONS : 300 GPM (BALANCED)



* - FLOW DIRECTION OBSERVED IN BOTH CLOCKWISE AND COUNTER CLOCKWISE DIRECTIONS.

Figure 16. Drawings of Combustor Flow Patterns, DP = -6.0 in.

COMBUSTOR DOME PLATE LOCATION: -6.0 in.
INLET CONFIGURATION : 45 DEGREES
FLOW CONDITIONS : 300 GPM (BALANCED)



LIGHT POSITION - 2.0 in. 3.0 in.

Figure 16. Cont'd.

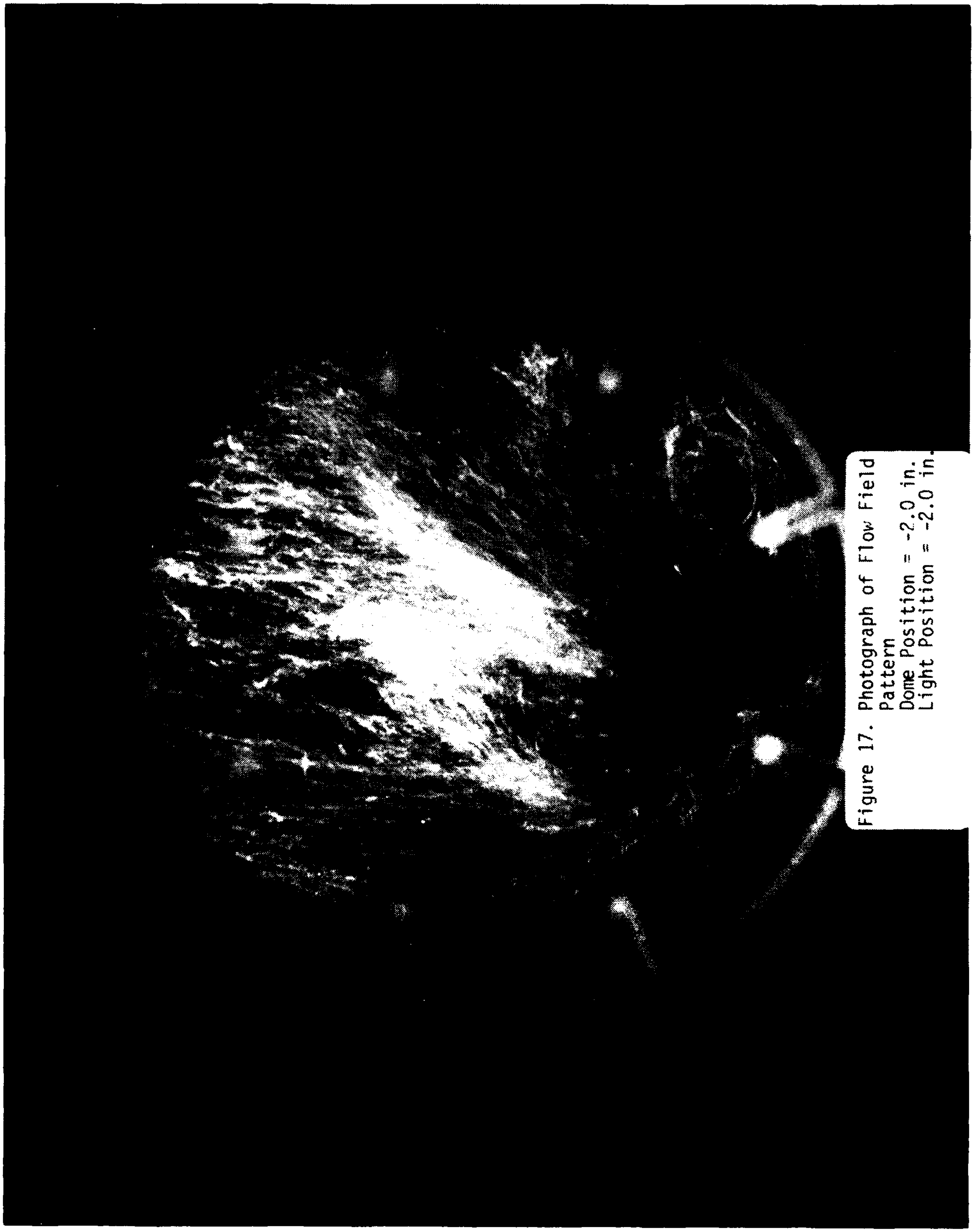


Figure 17. Photograph of Flow Field Pattern
Dome Position = -2.0 in.
Light Position = -2.0 in.

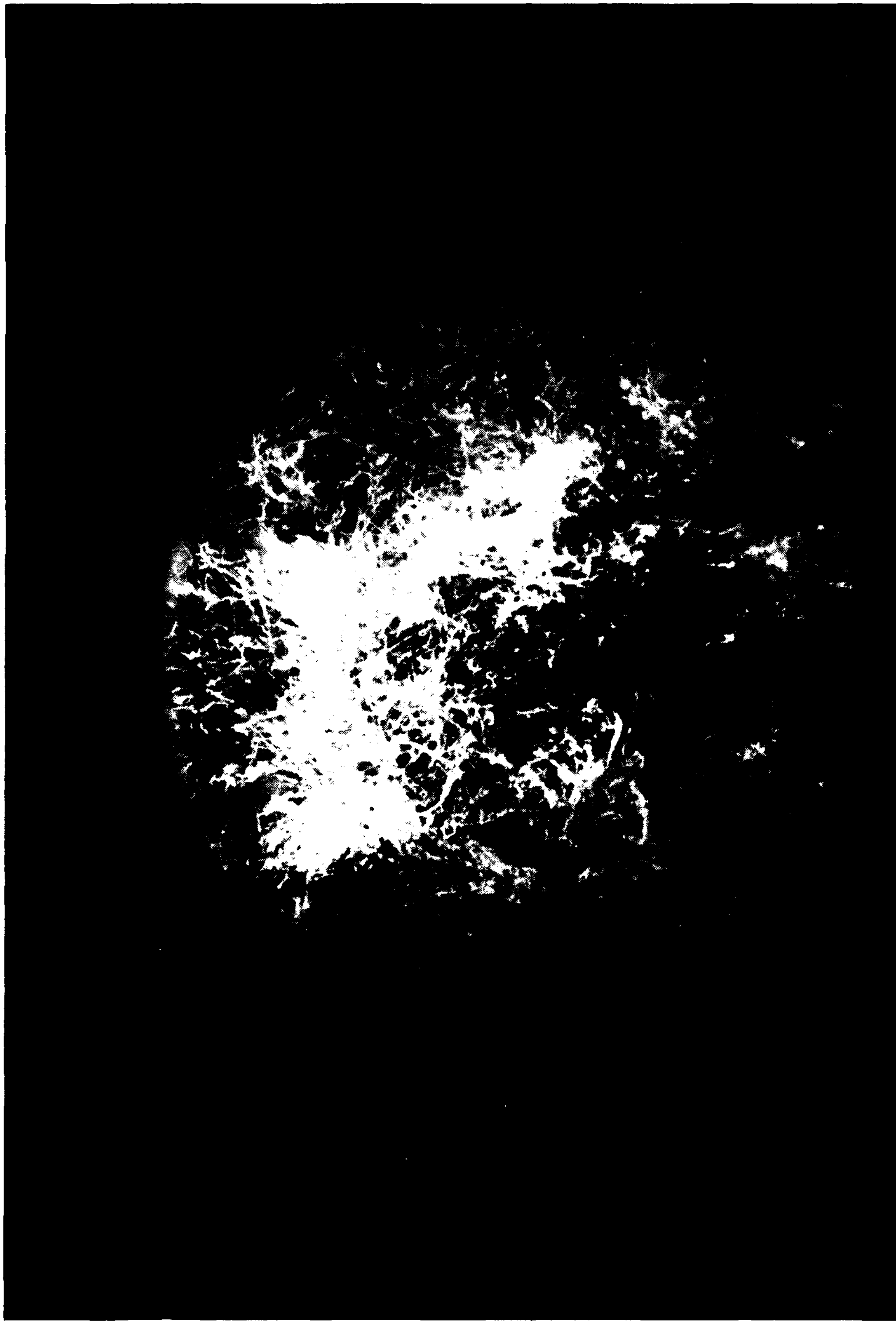


Figure 18. Photograph of Flow Field Pattern
Dome Position = -2.0 in.
Light Position = 0.0 in.

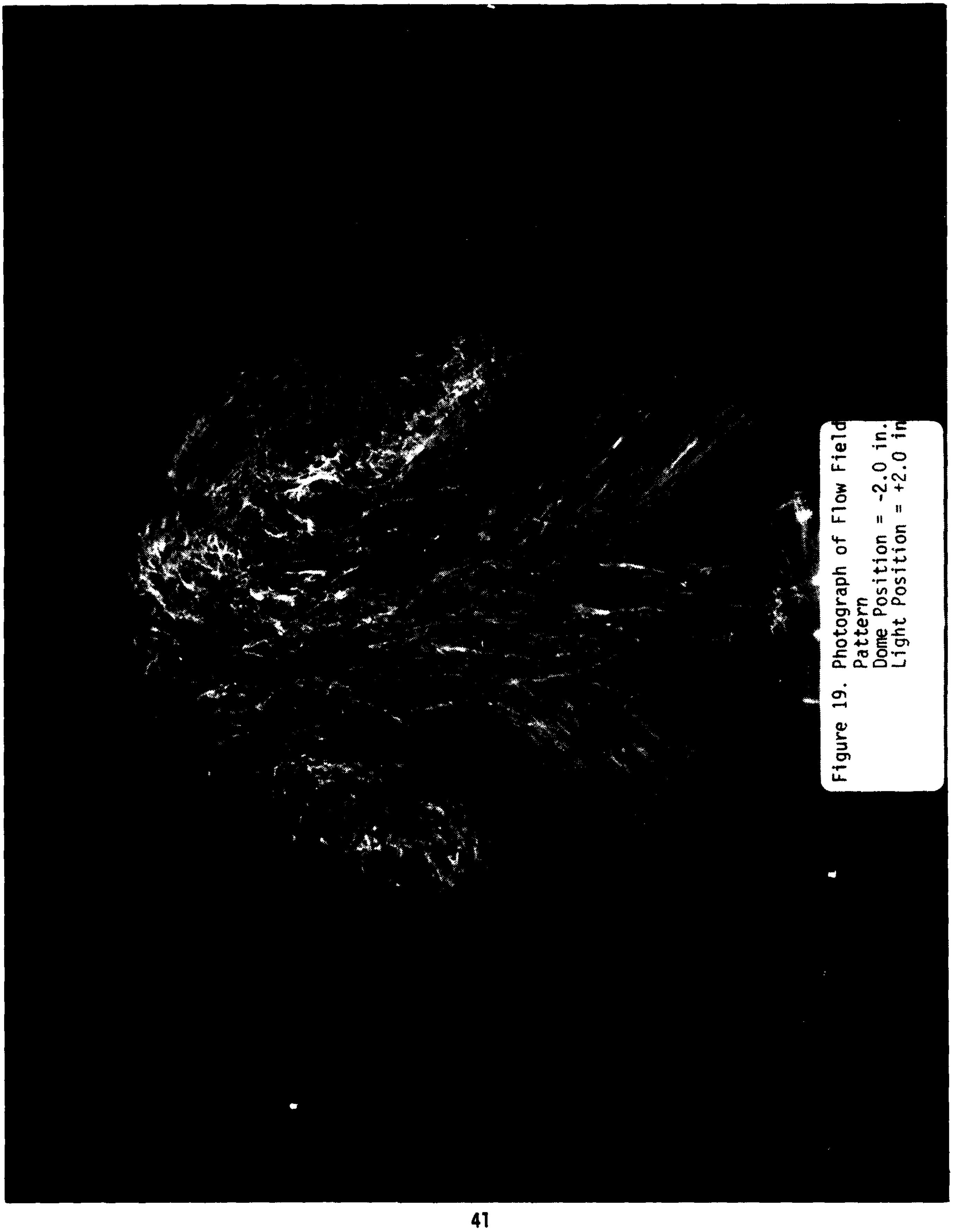


Figure 19. Photograph of Flow Field
Pattern
Dome Position = -2.0 in.
Light Position = +2.0 in

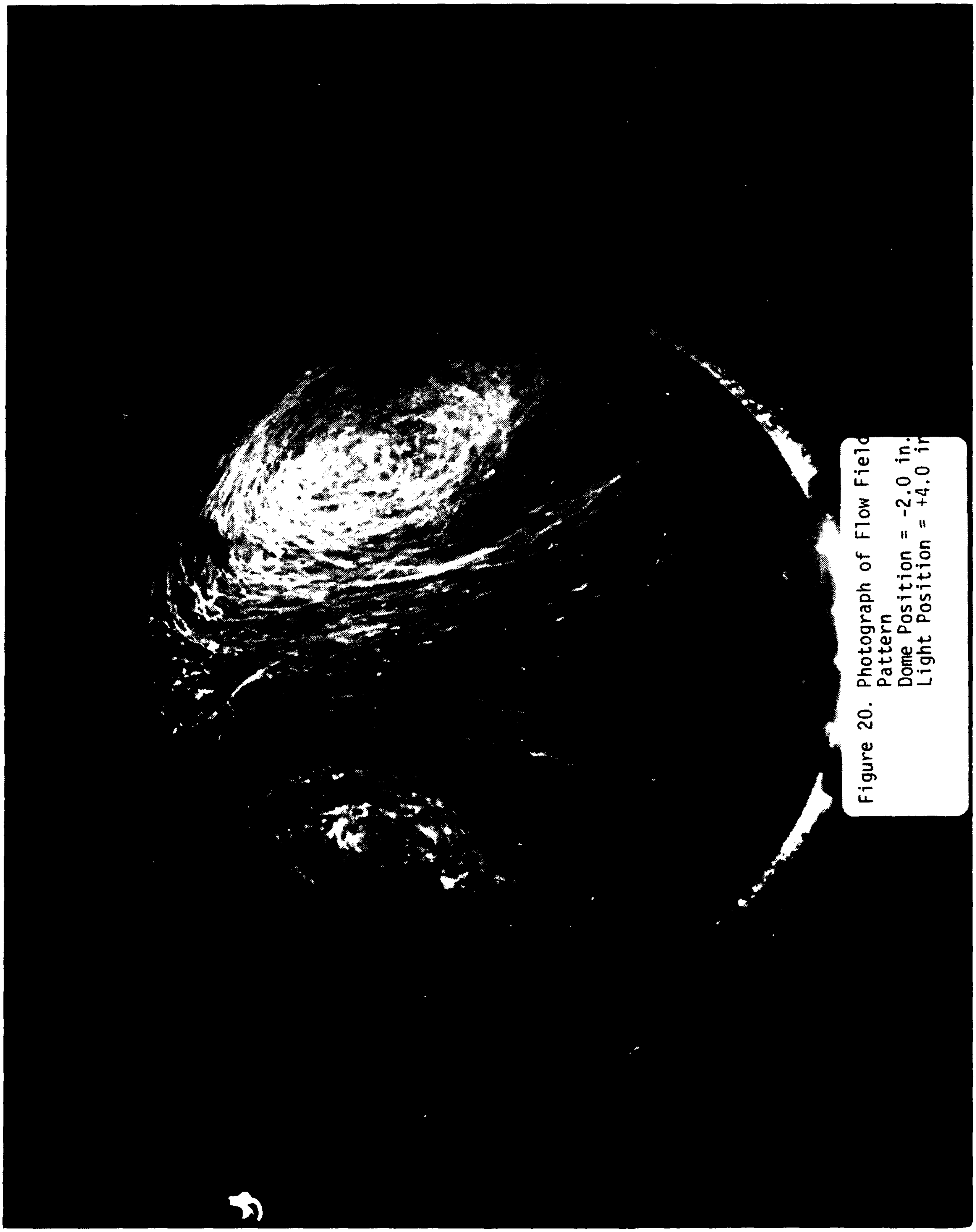


Figure 20. Photograph of Flow Field Pattern
Dome Position = -2.0 in.
Light Position = +4.0 in

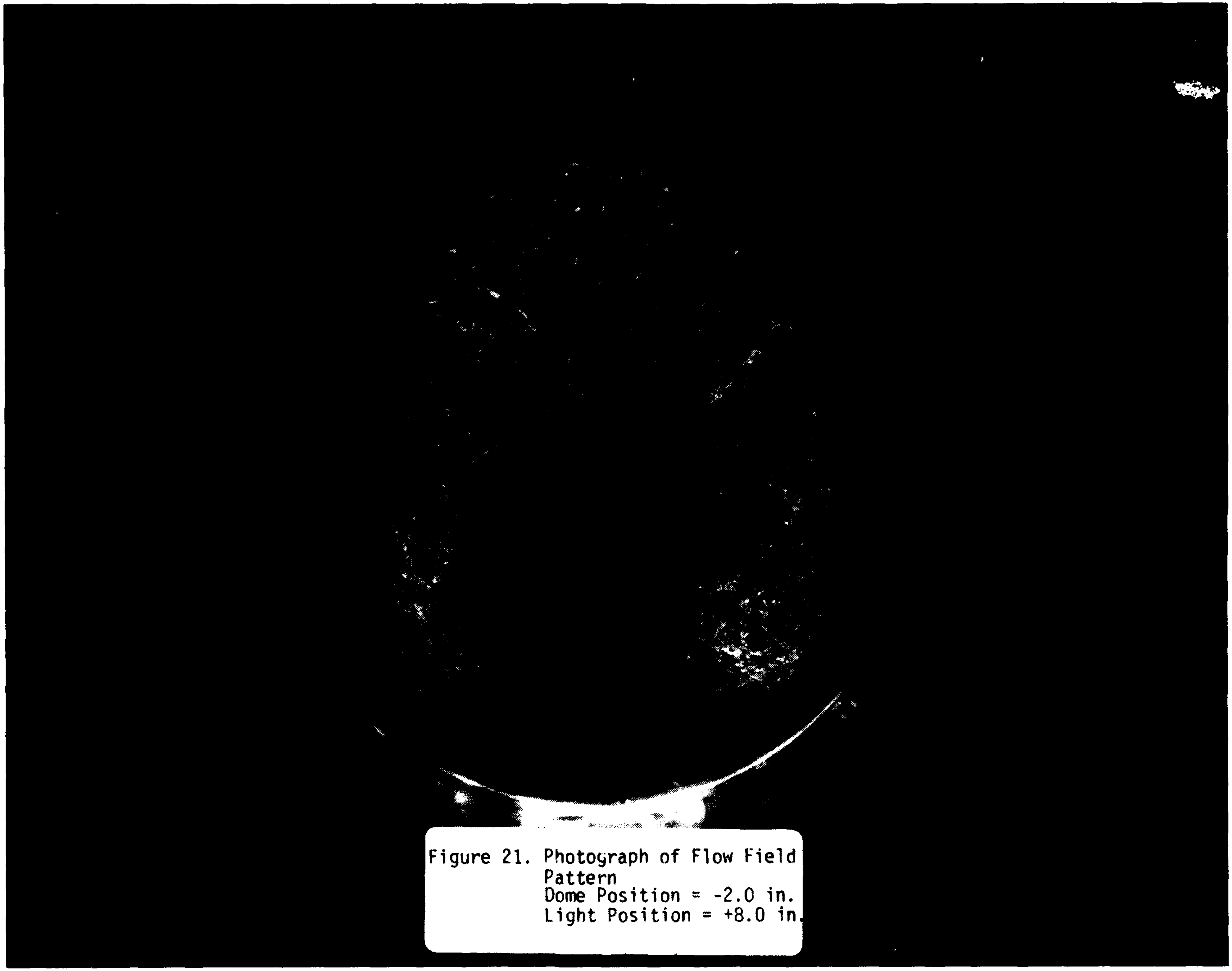


Figure 21. Photograph of Flow Field Pattern
Dome Position = -2.0 in.
Light Position = +8.0 in.

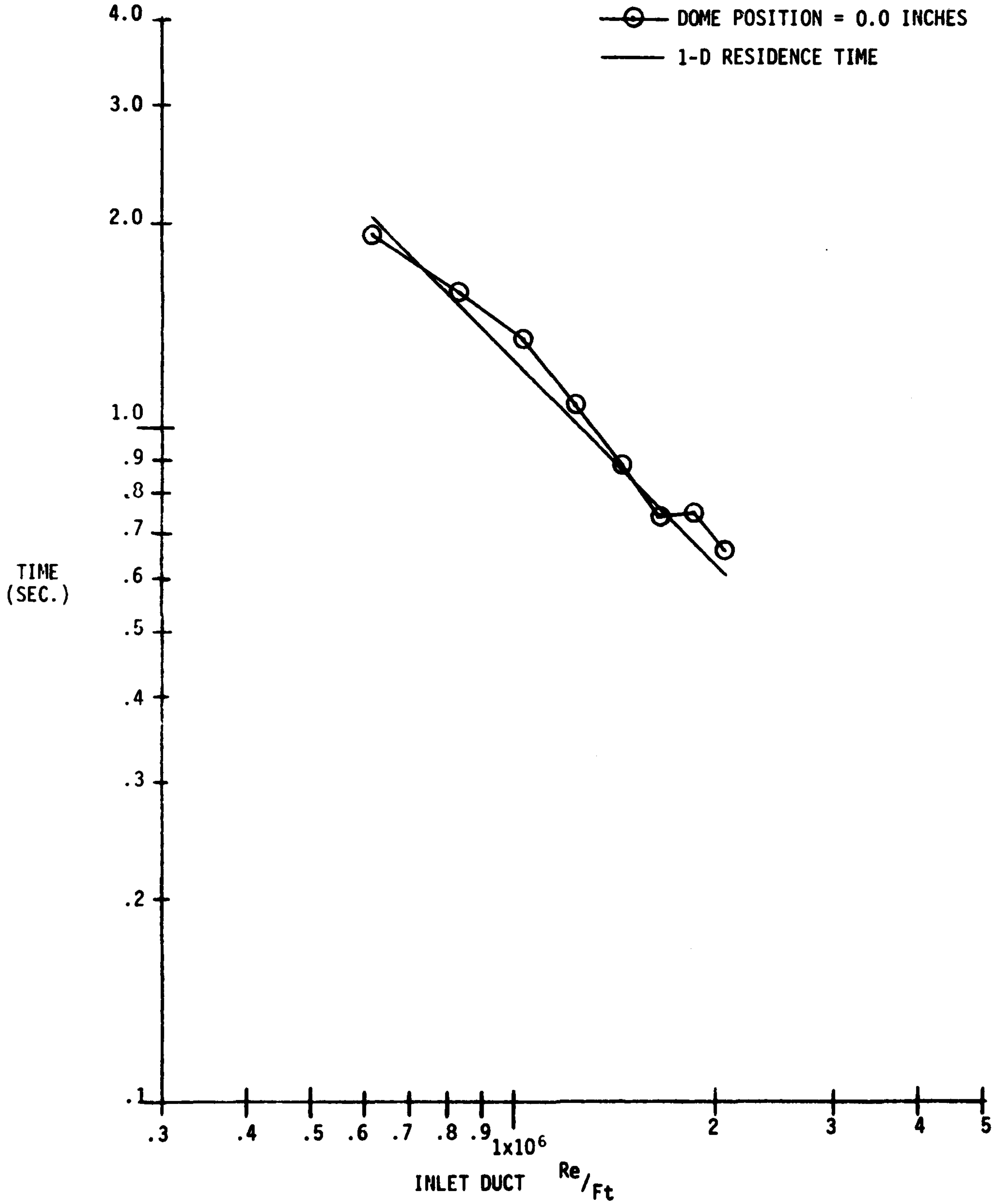


Figure 22. Residence Times Versus Inlet Flow Reynolds Number, DP = 0.0

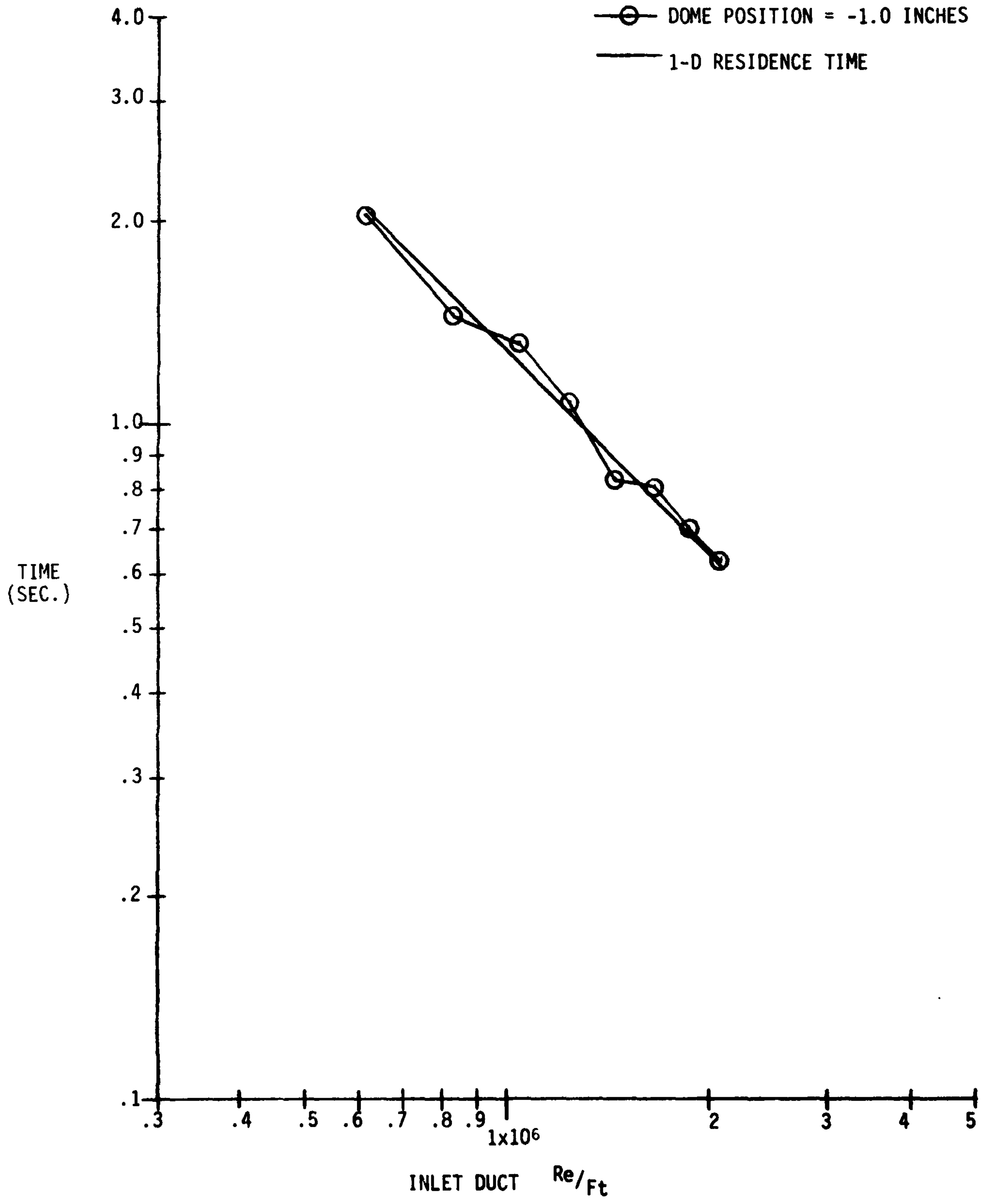


Figure 23. Residence Times Versus Inlet Flow Reynolds Number, DP = -1.0

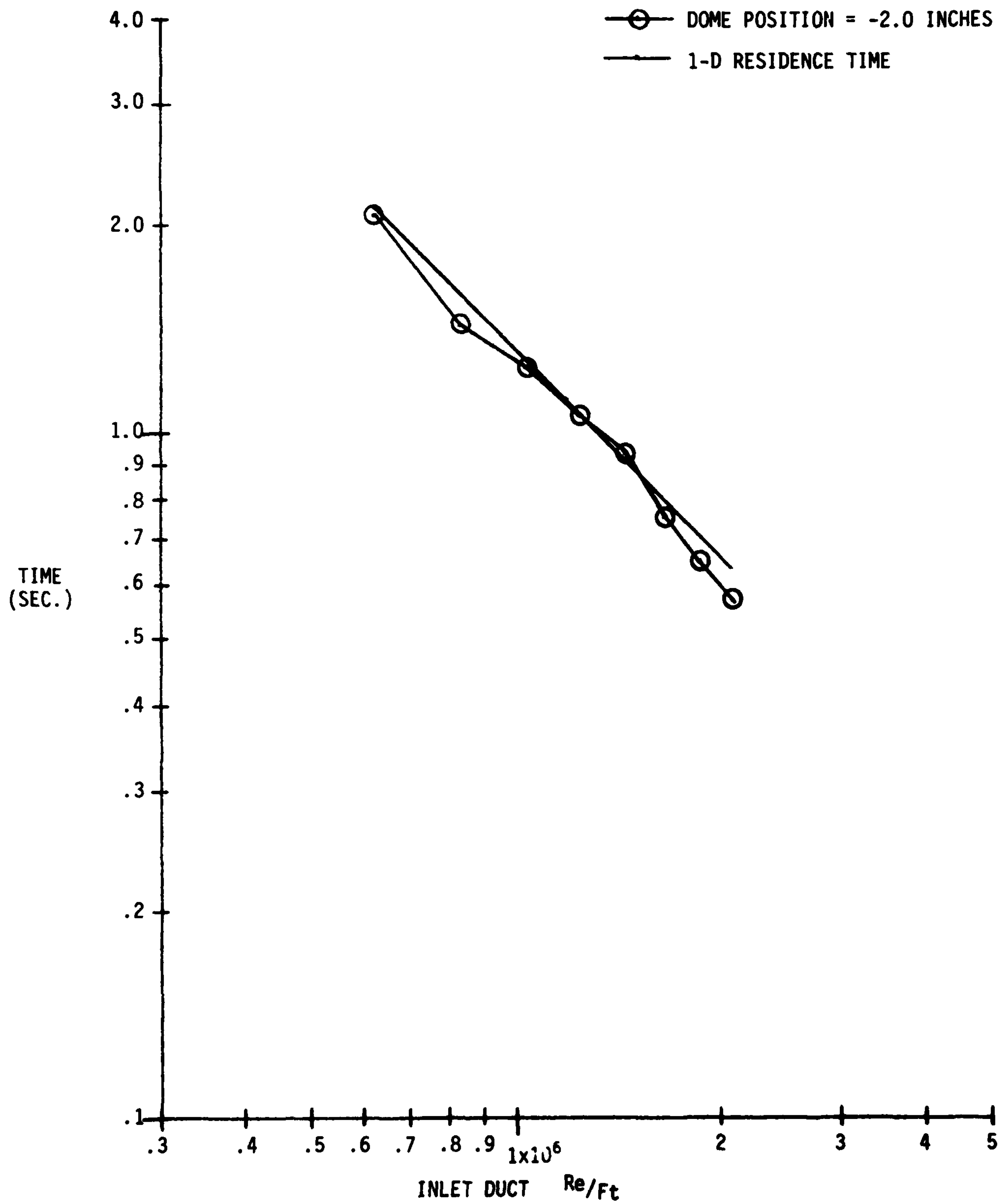


Figure 24. Residence Times Versus Inlet Reynolds Number, DP = -2

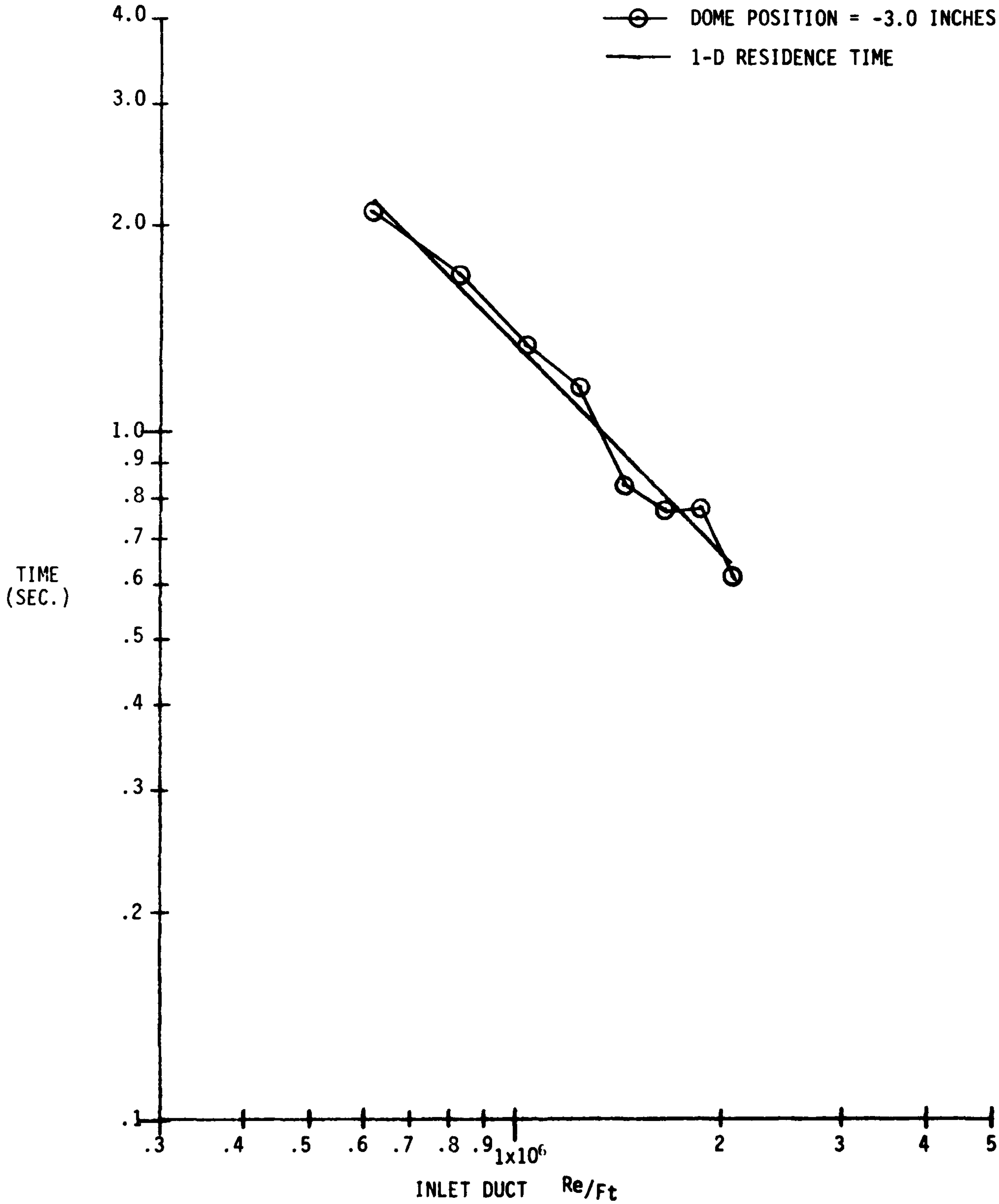


Figure 25. Residence Time Versus Inlet Reynolds Number, DP = -3

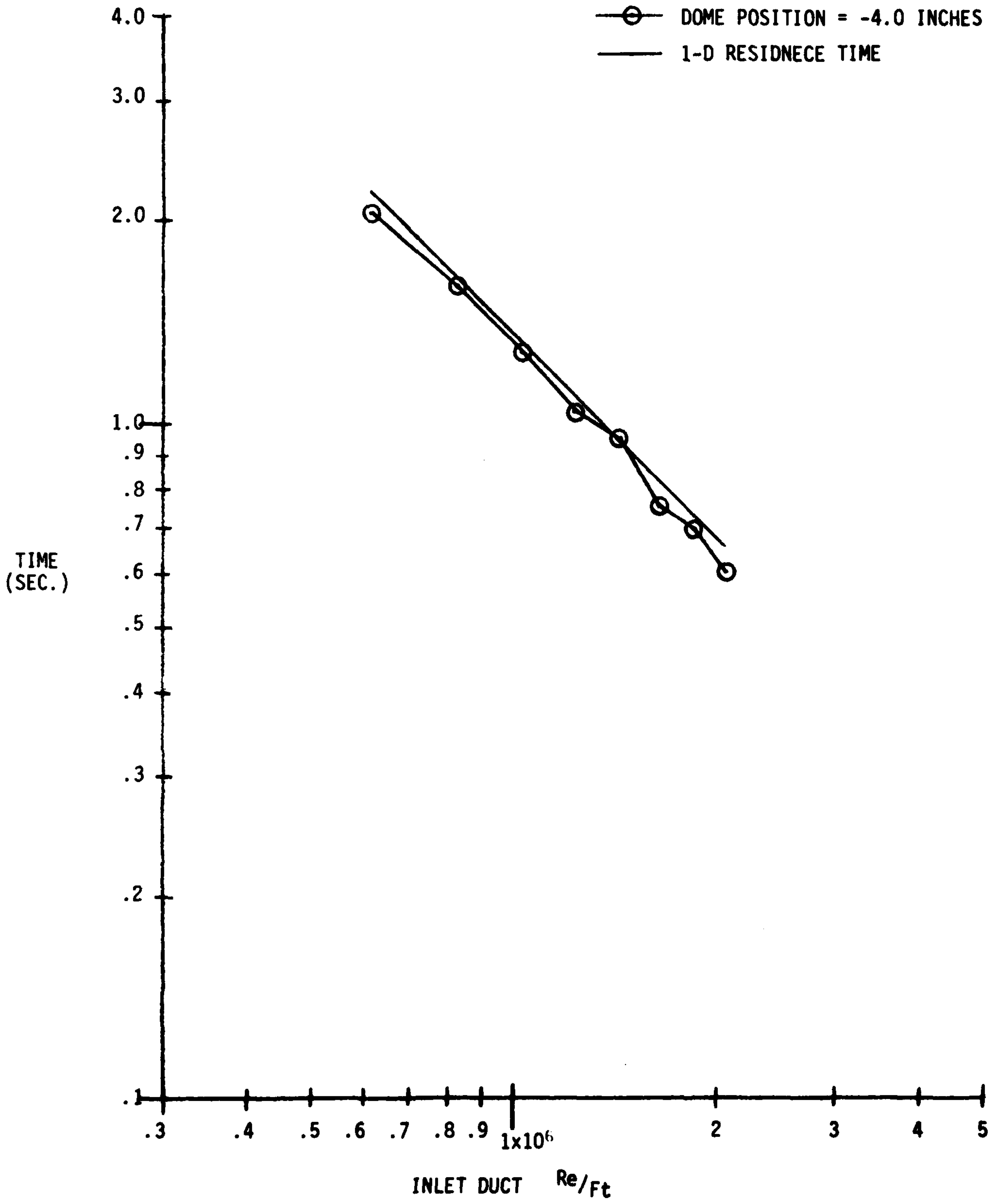


Figure 26. Residence Time Versus Inlet Reynolds Number, DP = -4

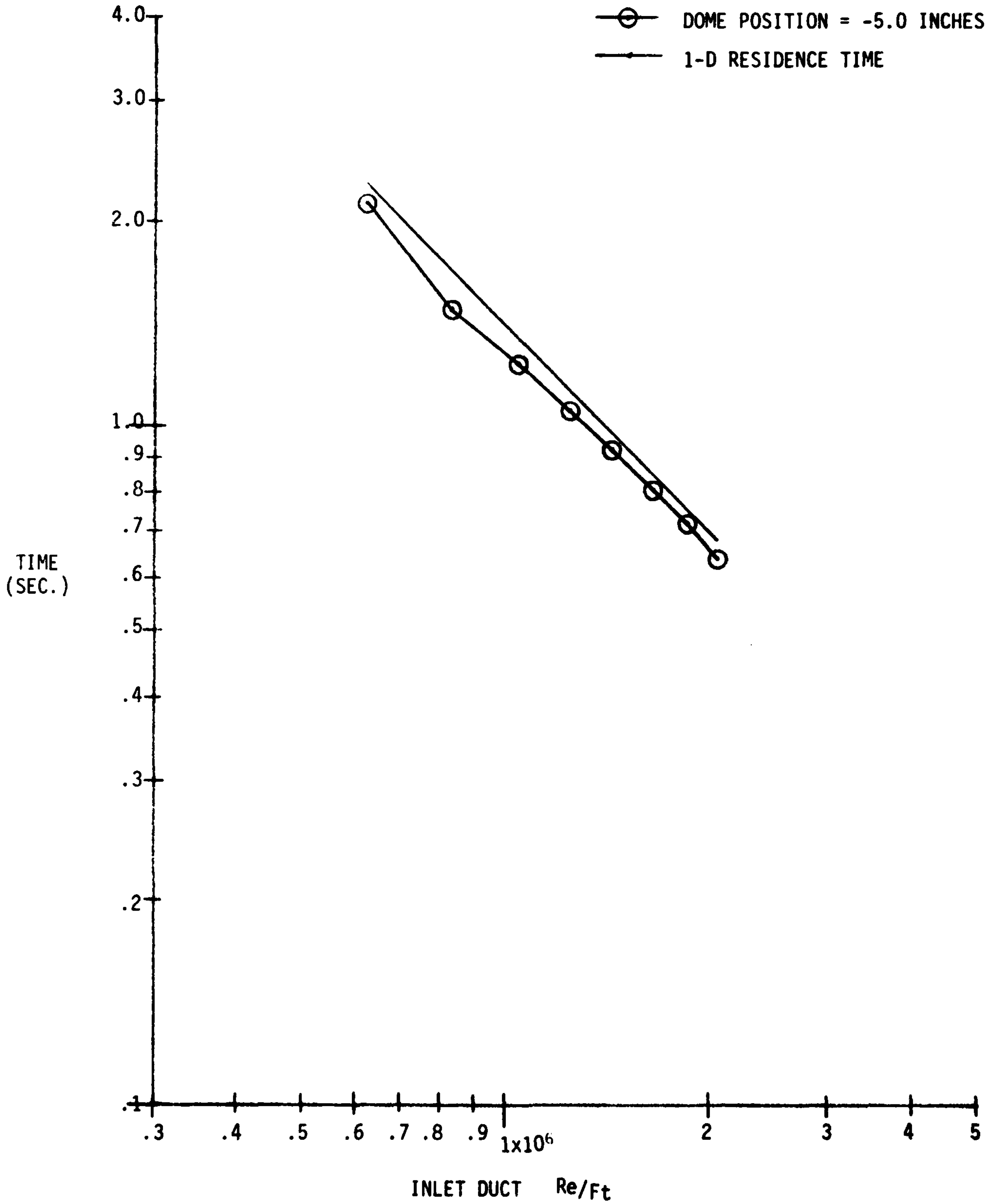


Figure 27. Residence Time Versus Inlet Reynolds Number, DP = -5

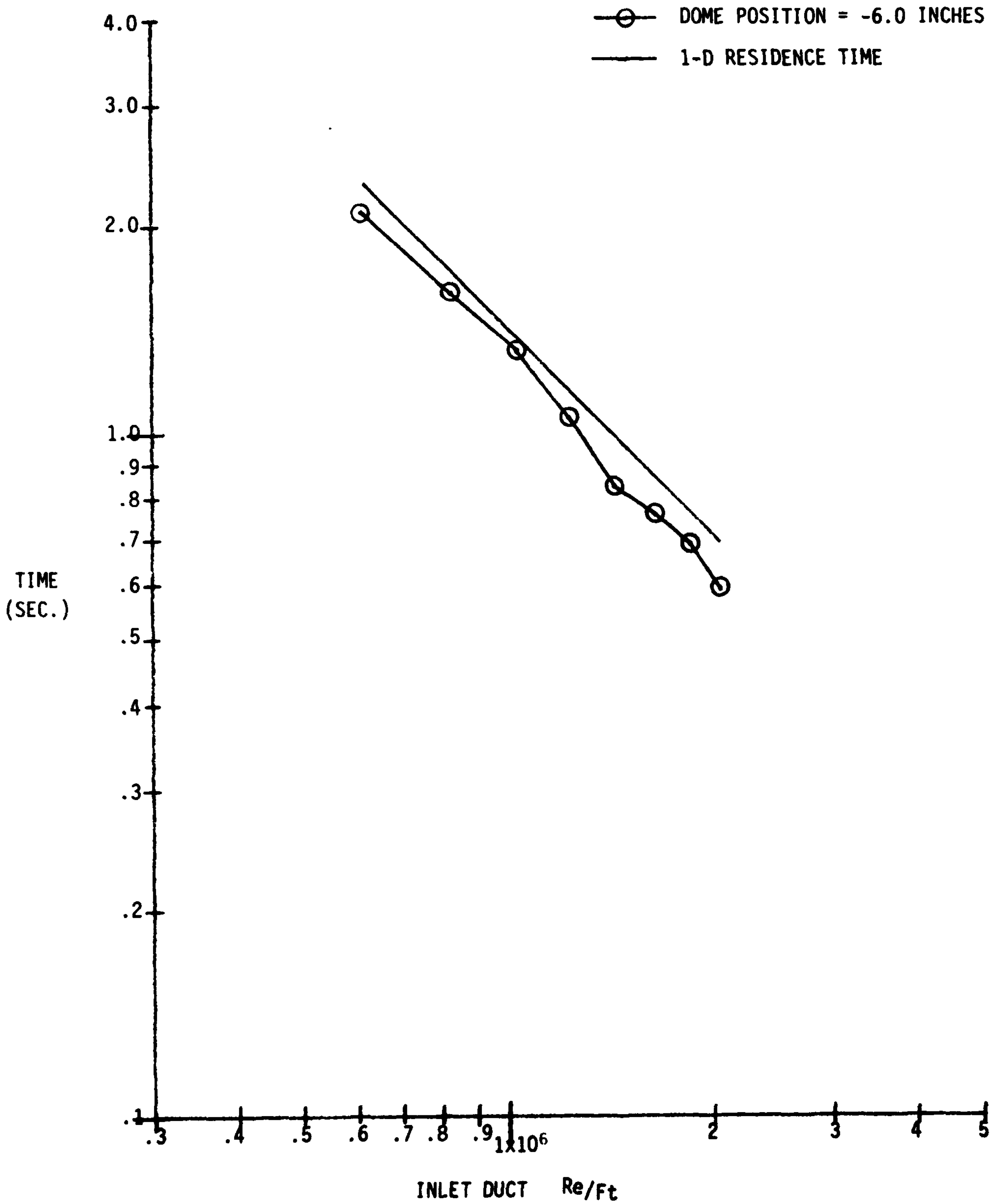


Figure 28. Residence Time Versus Inlet Reynolds Number, DP = -6

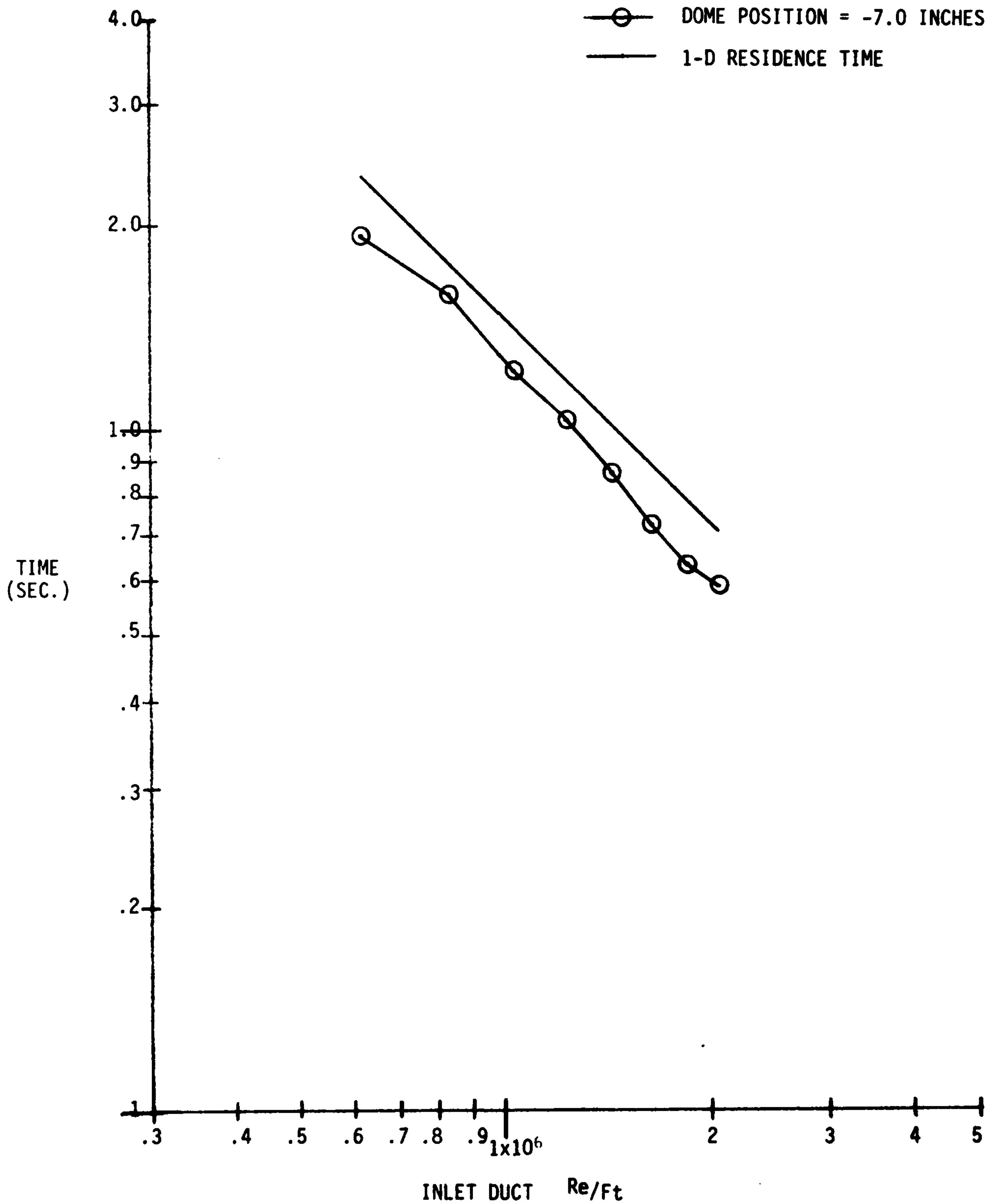


Figure 29. Residence Time Versus Inlet Reynolds Number, DP = -7

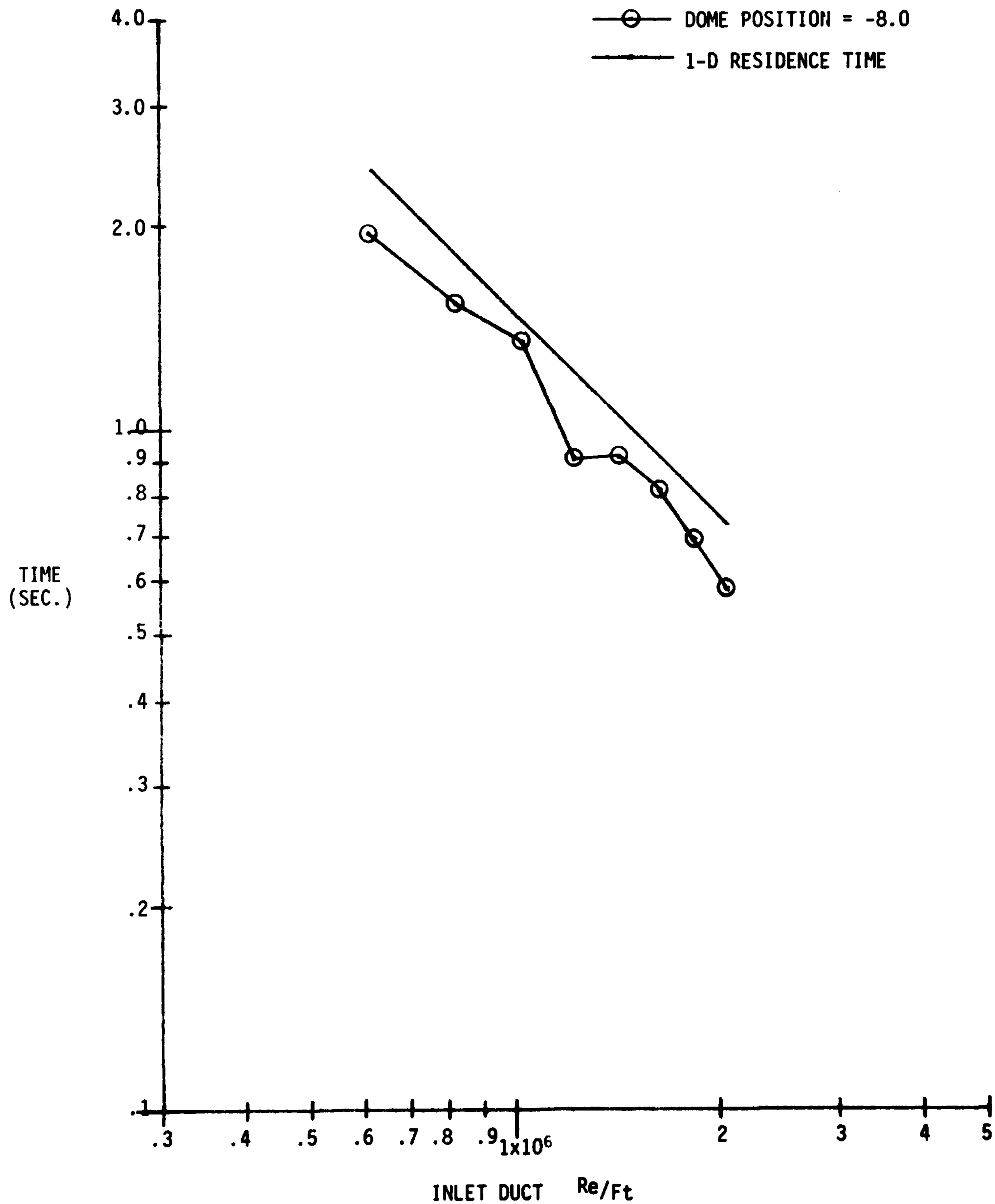


Figure 30. Residence Time Versus Inlet Reynolds Number, DP = -8

Table 3. Measured Residence Times

RESIDENCE TIMES (SEC.)

FLOW RATE GPM	150	200	250	300	350	400	450	500
DOME PLATE POSITION (in.)								
0.0	1.914	1.568	1.349	1.071	0.868	0.734	0.742	0.654
-1.0	2.043	1.445	1.317	1.067	0.827	0.806	0.700	0.628
-2.0	2.069	1.438	1.245	1.051	0.929	0.754	0.647	0.572
-3.0	2.100	1.695	1.342	1.152	0.837	0.769	0.779	0.614
-4.0	2.047	1.590	1.265	1.035	0.948	0.752	0.698	0.601
-5.0	2.127	1.483	1.239	1.050	0.922	0.807	0.720	0.638
-6.0	2.075	1.587	1.392	1.047	0.825	0.758	0.686	0.597
-7.0	1.921	1.577	1.220	1.038	0.862	0.725	0.633	0.587
-8.0	1.940	1.539	1.356	0.900	0.915	0.815	0.689	0.585

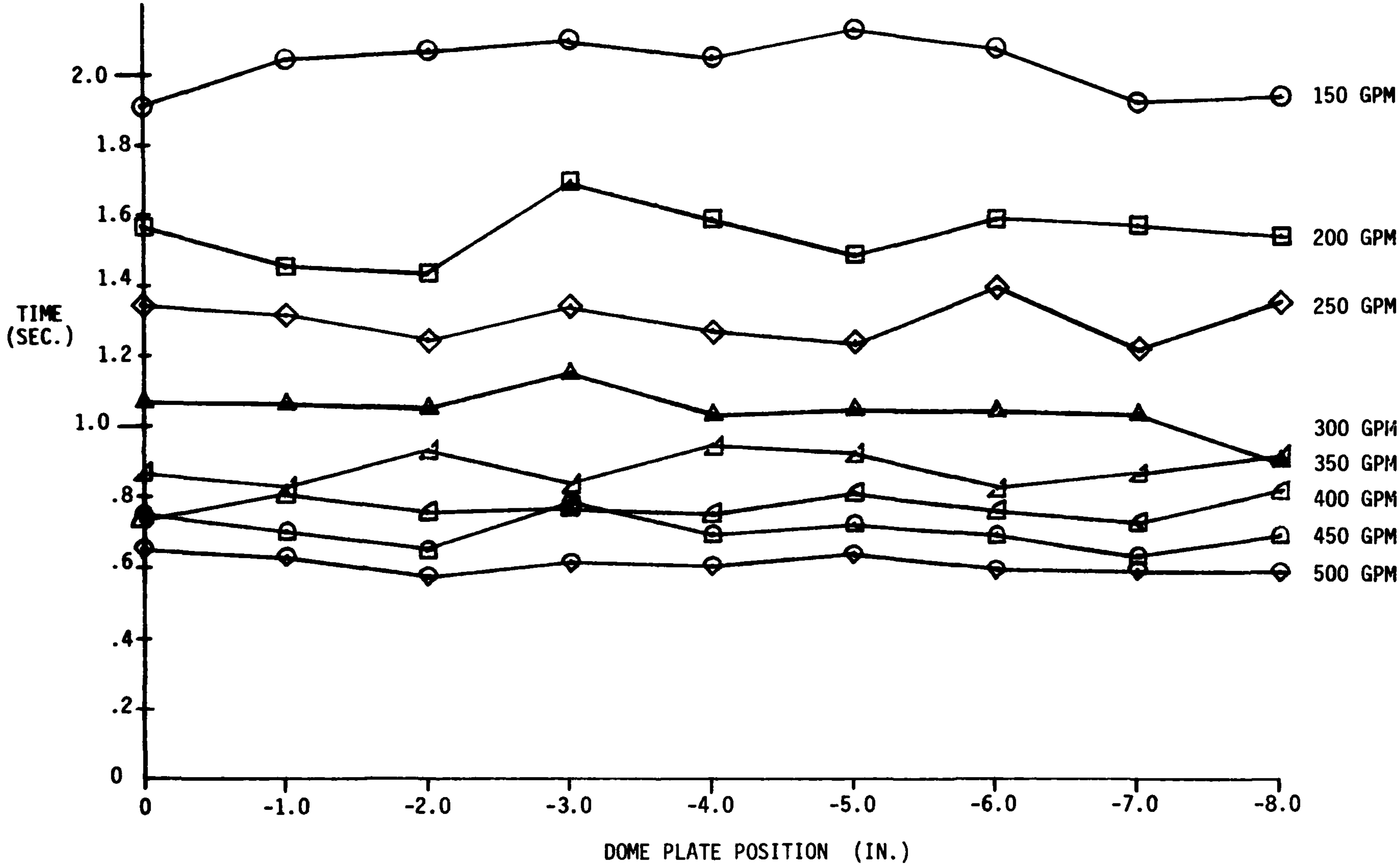


Figure 31. Residence Time Versus Dome Plate Position

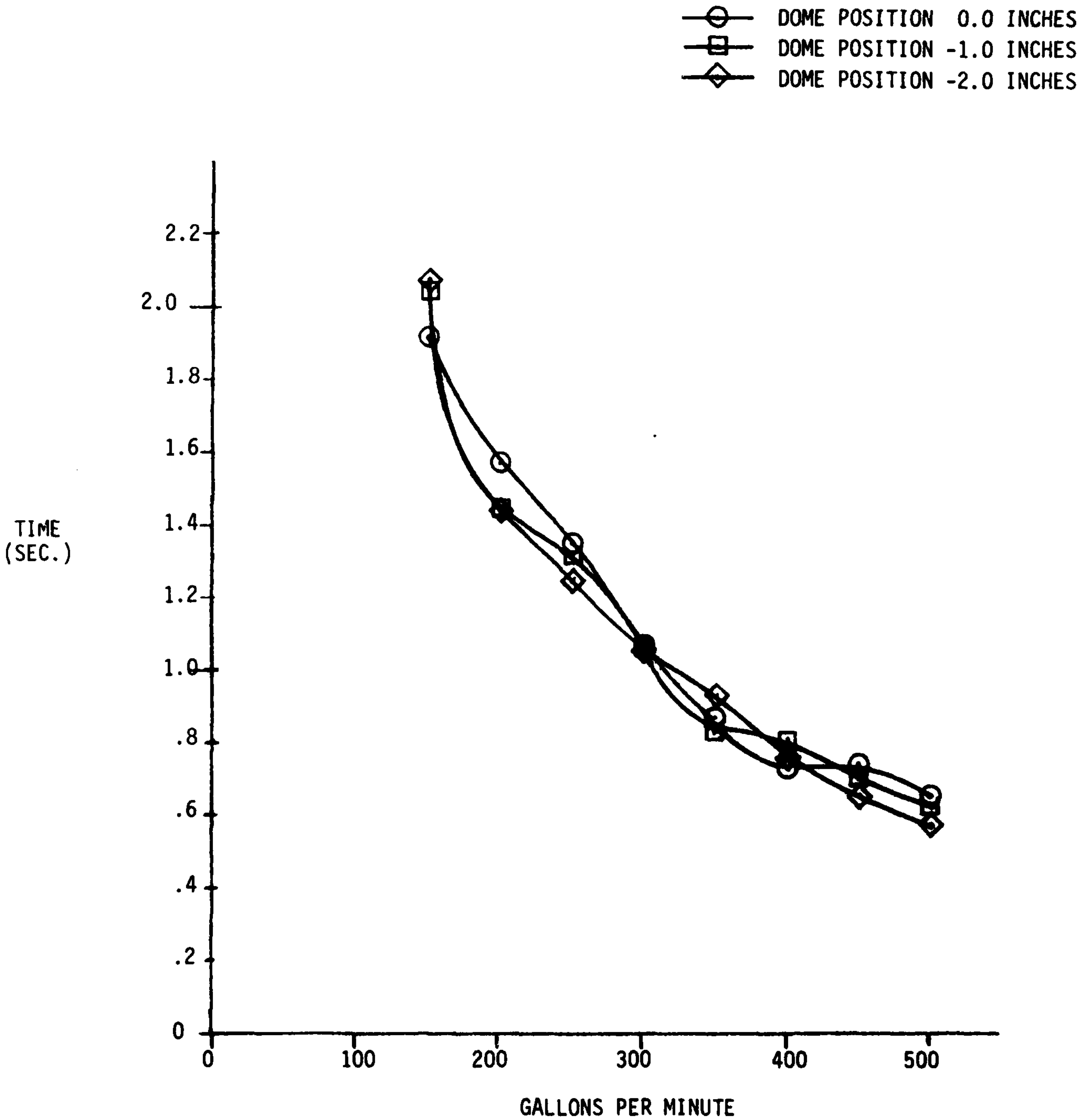


Figure 32. Residence Time Versus Total Combustor Flow Rate

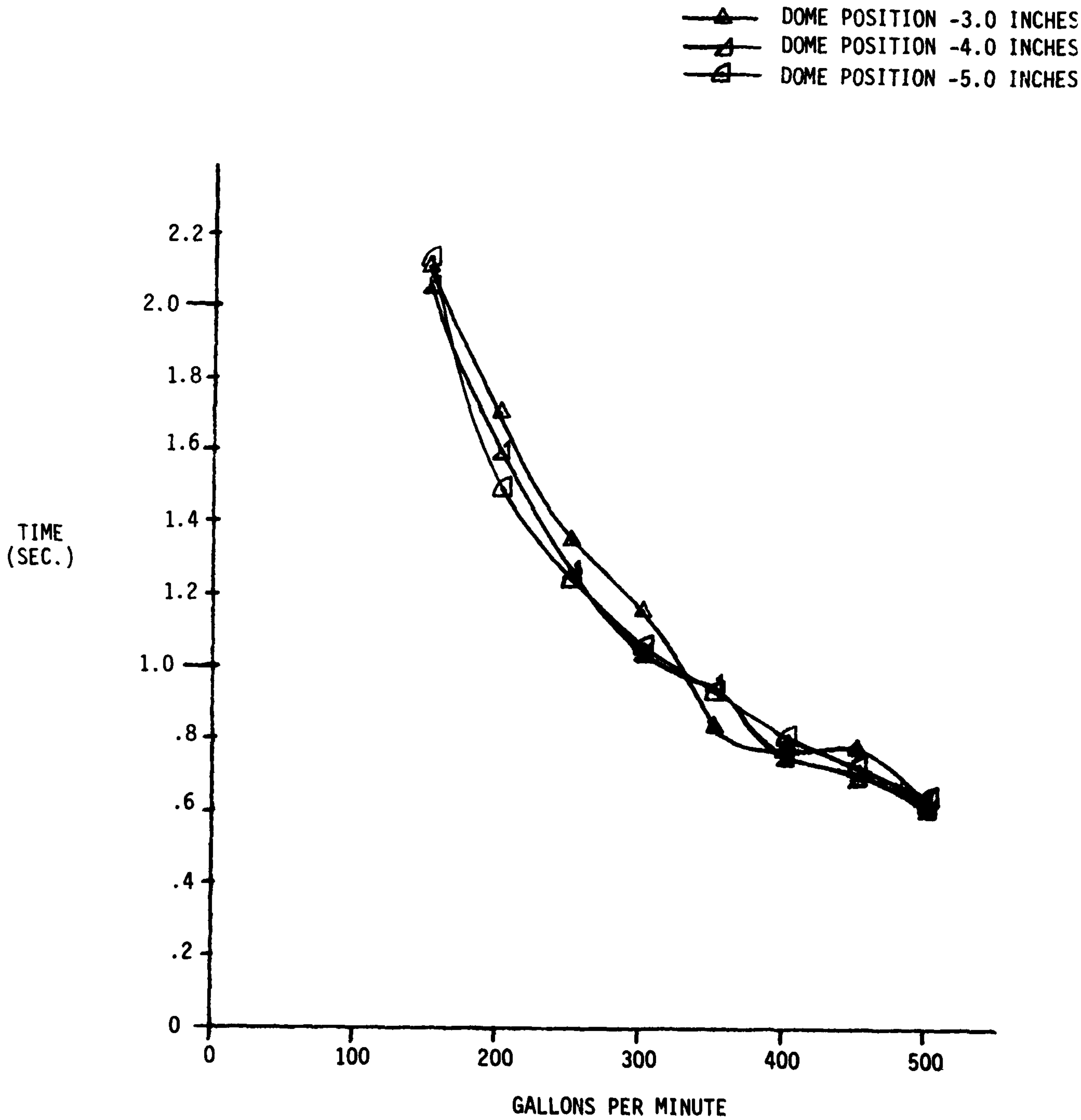


Figure 33. Residence Time Versus Total Combustor Flow Rate

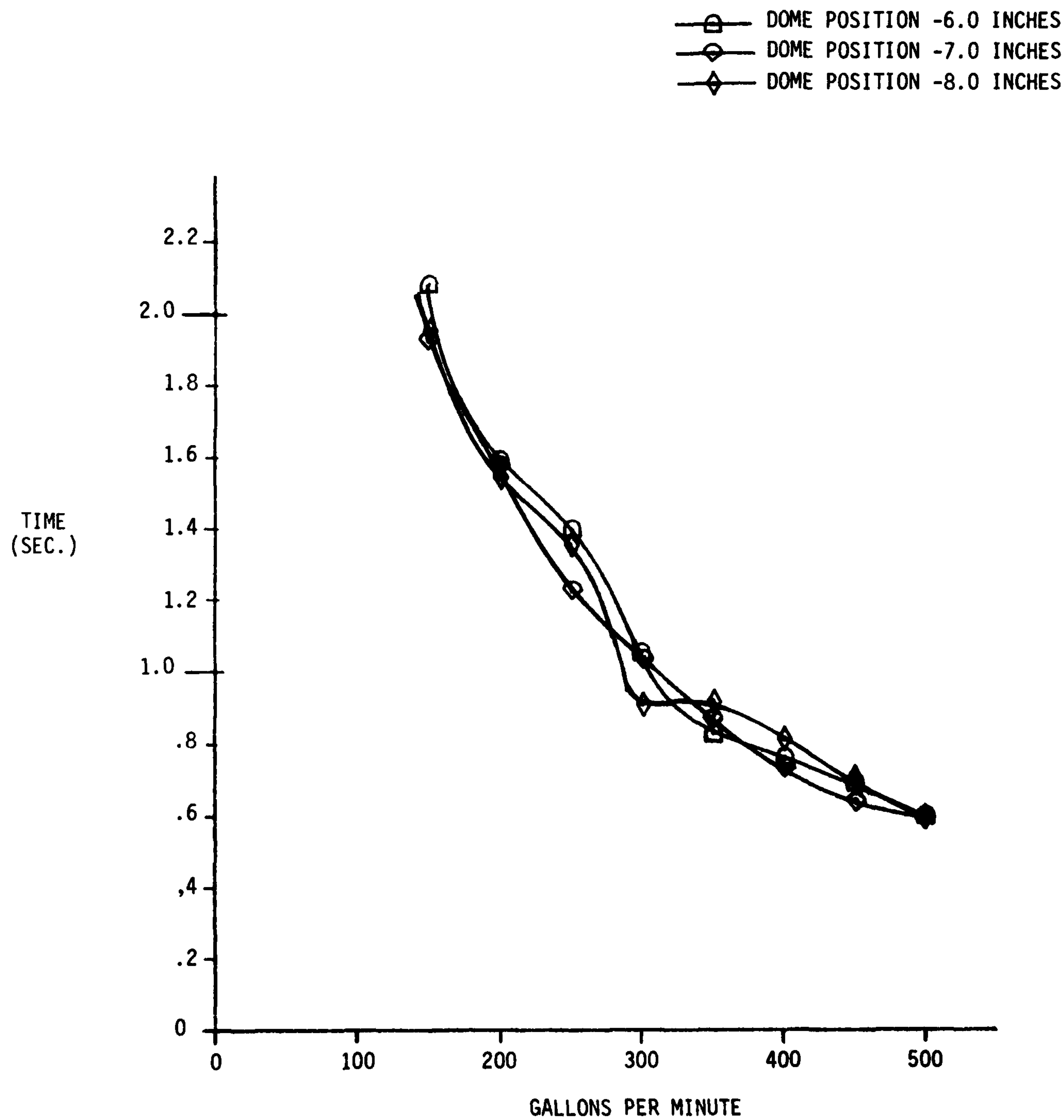


Figure 34. Residence Time Versus Total Combustor Flow Rate

Table 4. Inlet Duct Flow Conditions

WATER TUNNEL TOTAL FLOW RATE GPM	INLET DUCT FLOW VELOCITY FT./SEC.	INLET DUCT REYNOLDS NUMBER PER FOOT X10^{-6}
150	4.37	0.617
200	5.83	0.824
250	7.29	1.029
300	8.75	1.236
350	10.21	1.442
400	11.67	1.648
450	13.12	1.854
500	14.58	2.060

SECTION 10

TECHNICAL DATA SURVEY AND MATH MODELLING SUPPORT

An important aspect of multi-ducted inlet combustor research and development effort is to develope a mathematical model to describe flow field characteristics and predict performance parameters of combustor configurations. This effort will require support from several technical fields in order to arrive at a workable solution of the problem. This will be accomplished through the simulation efforts being conducted at the Water Tunnel test rig and through the fluid flow analysis and math modelling support efforts.

The effort undertaken here is directed toward identifying critical flow phenomena from the Water Tunnel Facility and defining the role of those phenomena in modelling the flow for the ramjet dump combustion configuration. The work performed to date (through 7/31/82) includes a review of current literature on ramjet combustor modelling and experimental work related to the present program, examination of flow visualization data from the Water Tunnel facility and identification of flow phenomena and parameters and their potential influence on one another. Descriptions of these efforts are presented in the following paragraphs.

10.1 Literature Review and Background

A brief literature review of ramjet technology was conducted at the beginning of the program. This review is not considered to have been exhaustive. Furthermore, additional papers, journal articles and other related technical literature are being reviewed as they are identified and become available. A bibliography of literature review to date is presented as the list of references at the end of this report.

While covering all aspects of ramjet technology to some degree, the literature review was directed primarily toward determining the current status of flow modelling in ramjet combustors. One of the main objectives was to identify significant flow phenomena and parameters which occur in the type of ramjet combustor configuration simulated by the Water Tunnel test facility.

This literature review has revealed that most ramjet modelling has been directed toward those configurations having an axisymmetric dump combustor. However the modelling approaches employed appear to have several features which can be readily adapted to various aspects of the flow configurations of the type simulated by the Water Tunnel test facility.

One modelling approach which appears to have some promise for the present configuration is the modular modelling techniques described by Edelman, et al in Reference 4. This approach assumes that the flow field can be broken down into separate zones, each of which can be investigated individually and then coupled together in some fashion through boundary conditions at the interfaces of the zones to obtain an overall method of evaluating the combustor flow field. The three major zones discussed in Reference 4 include a main directed flow, a recirculation region and a turbulent shear layer along a dividing streamline which separates the other two zones.

Amoung the more important parameters contributing to ramjet combustor performance is the "residence time". Roughly speaking this is the length of time that the mixed fuel and air molecules remain within a certain region of the combustor. Actually several different definitions of residence time were found in various references,[7,8,9] Most of

these definitions are formulated on the basis of the time required for a dye or tracer concentration in the combustor to decay to some percentage of its initial value. It was pointed out in Reference 7 that residence time depends solely upon vortex shedding, thus the vortex phenomena which occurs in the combustor becomes extremely important.

As the importance of vortex shedding became more apparent during the course of the literature review, simplified models of vortex flow were sought. Among the simplest flows which are driven by vortex shedding is the flow in a driven cavity. The collection of papers presented in Reference 10 gives a good accounting of numerical approaches to modelling driven cavity flows. It should be noted that the time which the fluid remains in the vicinity (residence time) is controlled by the vortex shedding frequency in this case as well. The applicability of the driven cavity modelling approaches to any aspect of the "side dump" combustor configuration has not been fully established. However the nature of the recirculating flow in the dome region of the combustor has sufficient similarity to the driven cavity to warrant further investigation.

Additional literature regarding other aspects of the flow is being reviewed. Among the flow phenomena addressed in these references are flow impingement on a solid surface and interaction of two adjacent streams.[11,12]

One document has been obtained which presents experimental data for a flow facility similar to the Water Tunnel test facility. This data was obtained in a water flow test facility at United Aircraft Research Labs. The facility, the data and the test procedure are described in Reference 8.

Additional literature are being sought which deals with the "side dump" combustor configuration and the various flow phenomena which occur in such a configuration.

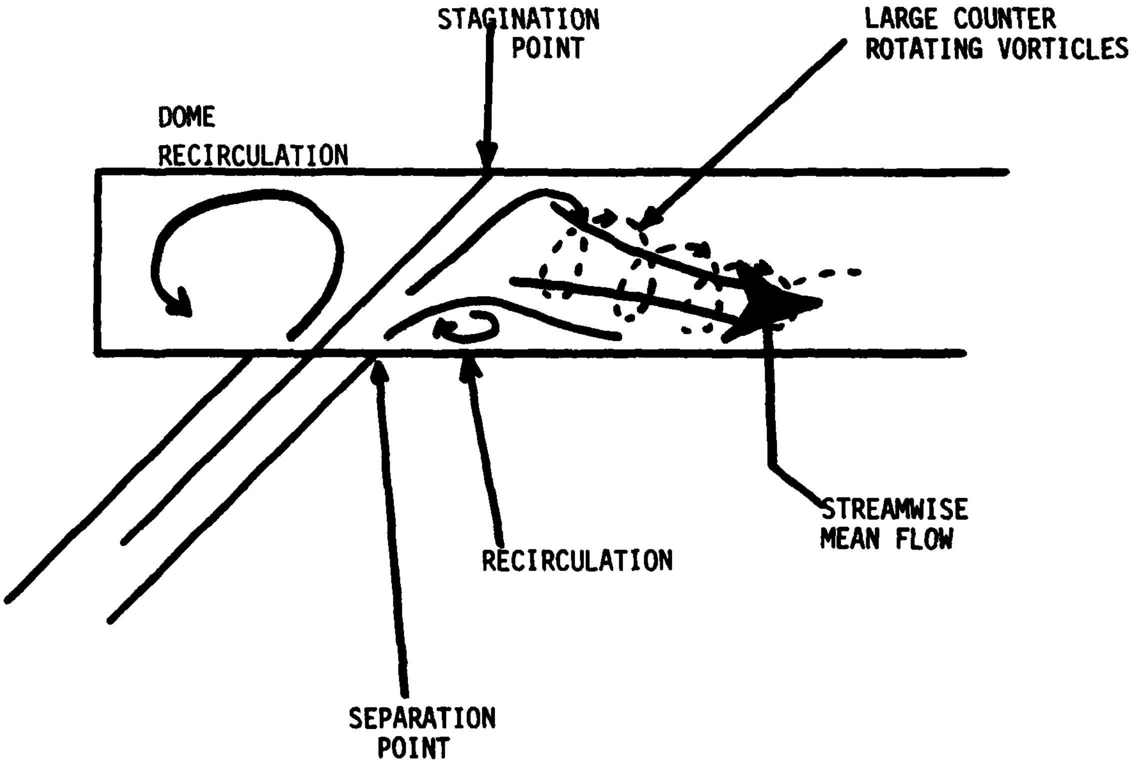
10.2 Significant Flow Phenomena and Related Parameters

Examination of flow visualization data from the Water Tunnel Facility revealed the existence of several different flow phenomena of the types discussed in the literature. Among these are primary and secondary vortex flow and recirculation regions, flow impinging against solid surfaces and stagnation point flows as well as interactions between these various phenomena. Associated with these phenomena are certain properties and parameters which quantify and determine the relative significance of the various types of flow. These include vortex shedding frequency, flow impingement angle and dividing streamline location, stagnation point locations and residence time, among others.

Some of these phenomena and the related parameters will be discussed briefly along with their potential significance in the present combustor configuration.

10.2.1 General Flow Character

The nature of the flow in the present configuration is such that it can be separated into separate zones as suggested in Reference 4. These zones are indicated in Figure 35. What appears to be three primary zones are: 1) a recirculating flow in the dome region of the combustor, 2) two counter rotating helical vortices trailing in the streamwise direction from the inlet, and 3) a mean flow component in the streamwise direction. In addition to these, there are several other flow zones which have been categorized as secondary flows, at least until more is known



Fiqure 35. Combustor Circulation Zones

about their significance. These secondary flows include a pair of small counter rotating vortices at the bottom of the combustor. These vortex flows are associated with the stagnation points resulting from the flow impingement on the walls of the combustor. ... her secondary flow is the recirculating flow immediately downstream of the inlet on the bottom side of the combustor. This recirculation region is the result of flow separation due to the inlet flow configuration.

The significance of these secondary flows will have to be determined from the modelling and analysis of the flow. There may also be additional regions of secondary flow present which have not yet been identified.

10.2.2 Dome Region

The recirculating flow in the dome region is reminiscent of the flow in a driven cavity. This is due to the fact that the dome region is filled by a portion of the inlet flow which is controlled by the position of the dome plate and the inlet angle. The volume of fluid in the dome region will increase until a certain limiting pressure is reached, at which point there will be an outflow from the dome reducing the dome pressure to a lower limit. This cycle will tend to repeat itself continuously with a periodicity related to a vortex shedding into the dome. The frequency of the vortex shedding is once again controlled by the inlet angle, the dome plate position, and the inlet flow velocity.

The fluid in the dome region will have associated with it a residence time which is controlled by the vortex shedding frequency. Basically this is the length of time the fluid particles remain in the dome region . This dome residence time will contribute to the overall

combustor residence time to some degree. The significance of this contribution must be determined from modelling.

The discussion of flow in the dome region given here assumes no simulated fuel flow from the back of this region. This assumption is made throughout this report because the presence of such flow will most likely change the overall character of the combustor flow significantly.

10.2.3 Streamwise Flow

As a result of the arrangement of the inlet configuration, a complex system of vortices exists in the streamwise direction. This system consists of two large counter-rotating helical vortices, each bounded by the plane of summetry and the main circular duct walls. The vortex system also includes a pair of small counter-rotating vortices located at the top of the main circular duct. These are well downstream of the inlet.

This system of vortex flow is separated from the dome flow by a dividing streamline whose location is located and controlled by the inlet duct angle. This is illustrated in Figure 36. The dividing streamline divides the flow which goes into the dome from that which goes downstream. As a first approximation, the flow impinging on the combustor duct wall is treated as a two dimensional jet against an inclined plate as described in Reference 11. According to the principal of continuity.

$$\rho u A = \text{const.}$$

where ρ = density, u = velocity and A = area. Using this principle, the flow impingement against the top of the circular duct and the dividing

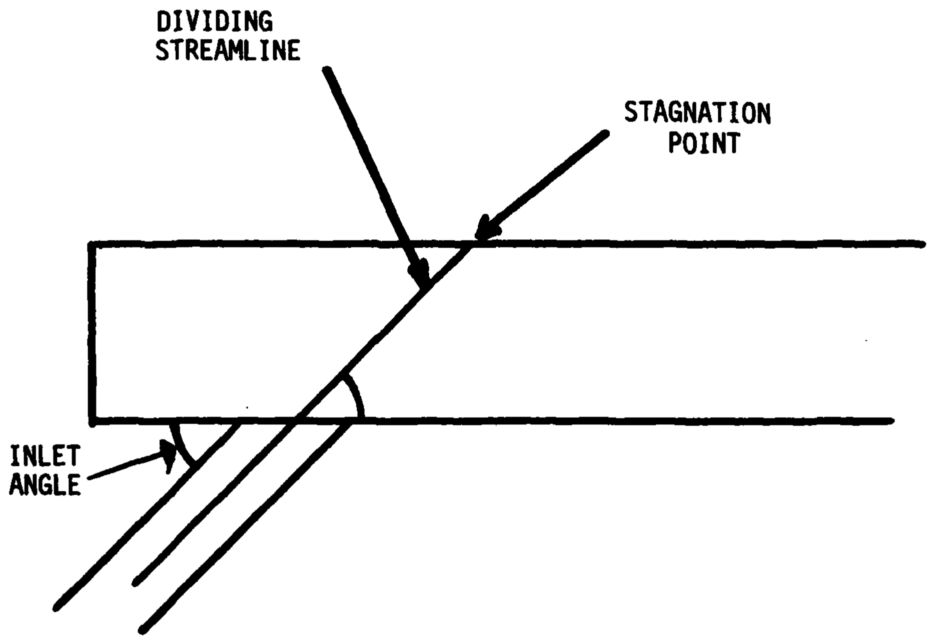


Figure 36. Combustor Dividing Streamline

streamline are indicated in Figures 36 and 37. From Figure 37, the mass flow away from the dividing streamline in both the upstream and downstream directions can be determined as in Reference 11 by using the relationships

$$A_1 = A\,\frac{1 + \cos\alpha}{2}$$

and

$$A_2 = A\,\frac{1 - \cos\alpha}{2}$$

The first of these expressions is used to determine the mass flow in the streamwise direction while the second expression is used to determine the mass flow into the dome region.

It is seen from the relationships that the portion of the mass flow which goes in each direction is controlled by the angle of the inlet ducts. The inlet duct angle which is the same as the flow impingement angle controls the dividing streamline, and the stagnation point location. In addition, the angle that the inlet ducts make with the combustor contribute to the vortex shedding frequency in the dome recirculation region as well as the cycle frequency of the streamwise helical vortices.

In addressing the streamwise behavior of the helical vortices downstream of the inlet, it was noted from the flow visualization data that the centers of the two vortices are nearest to the top of the combustor duct at the downstream lip of the inlet. In moving in the streamwise direction from the inlet, the vortex center gradually drops toward the bottom of the combustor duct and the vortex strength is dissipated. This is indicated by the fact, that at stations far downstream from the inlet the vortex flow remains only in a small portion of the combustor cross section near the bottom. This indicates that the mean flow dominates the

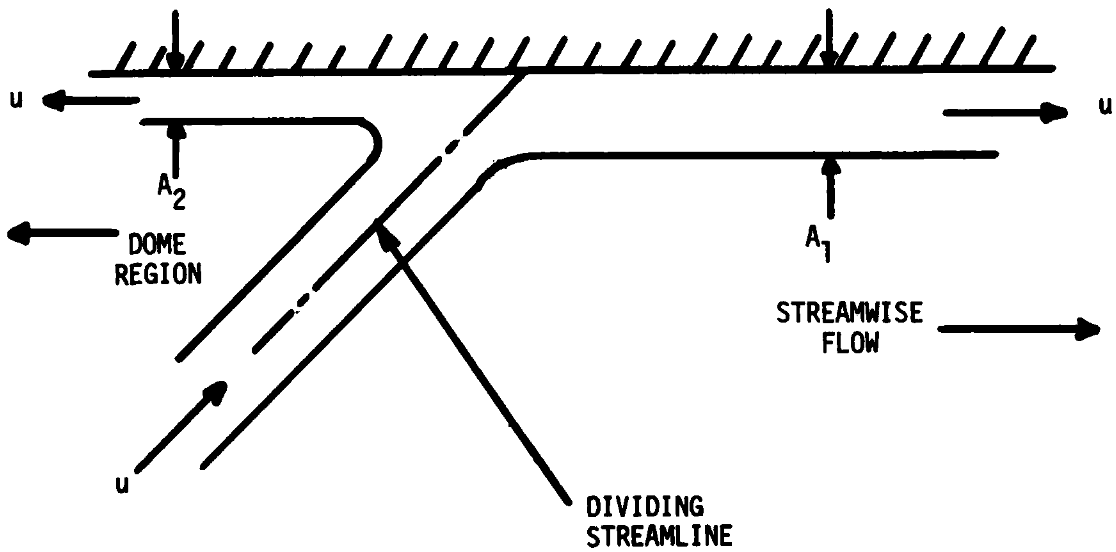


Figure 37. Impinging Jet Dividing Streamline

combustor cross section after some distance downstream of the inlet, while at the inlet the dominant helical vortex motion is superimposed on the mean streamwise flow.

At the inlet, the mean streamwise flow is a function of the component of the inlet flow along the combustor axis. Immediately downstream of the inlet is a region of separated recirculting flow occupying approximately the bottom third of the combustor duct. This restricts the actual steamwise component of the flow to the upper two-thirds of the combustor. At some point down-stream (within a combustor duct diameter), the separated flow reattaches and a streamwise component of the flow exists across the entire cross section.

Another important aspect of the inlet flow is the fact that the two streams are entering the combustor duct at an angle of 90^{o} to one another, and thus, there will be a strong interaction between the two steams. In this interaction, there is an initial dividing streamline situated in a vertical plane along the duct axis. Note that this is not the dividing steamline discussed previsously. This dividing steamline separates the two large counter-rotating helical vortices which are, in fact, the direct result of the interaction of the two inlet streams and the subsequenct impingement at the top of the combustor duct.

There is yet another element of the flow in the streamwise direction which may be extremely important. That is, the boundary layer flow along the combustor duct wall. The details have not been examined carefully at this time, however, this is planned in the near future.

10.2.4 Summary of Residence Time Definitions

As noted in earlier discussions, several different definitions of residence time have been encountered in the literature. No judgement has been made at this time as to which (if any) is best. In fact, it would appear that in the present complex flow field there will be several aspects of the flow which will contribute to a composite or new definition of residence time expressly for the configuration at hand.

It is believed to be worthwhile here to at least list the more important definitions present in the literature. From Reference 7:

$$t_r = 10\ (L/\sqrt{fk})$$

where f is the vortex shedding frequency, k is the strength of the fully formed vortices and L is the length of the formation region. From Reference 8, "one dimensional" residence time:

$$t_r = \frac{V}{\dot{V}}$$

where V is the total volume of fluid within the combustion chamber and $\dot{V}$ is the total volume flow rate entering the combustor. From Reference 9,

$$t_r = \frac{L}{v_d}$$

where t_r is the residence time of a foreign gas in a recirculation region, L is a characteristic length for diffusion and v_d is the diffusion velocity of the foreign gas.

As indicated previously, the residence time for the present configuration will be dependent upon the influence of several different aspects of the flow and consequently an expression for the total residence time must account for the different phenomena involved. This is presently being investigated and is pending residence time data from the test facility

SECTION 11

CONCLUSIONS AND RECOMMENDATIONS

Because only preliminary investigations of the multi-ducted inlet combustor configuration have been conducted, no firm conclusions can be formulated regarding residence times and water simulations related to actual combustor performance at the present time. Conclusions that are presented are of testing techniques and procedures utilized and the methods for obtaining visual information to aid flow analysis. Recommendations are also presented for incorporation into the continuing test program for the Water Tunnel test rig facility.

11.1 Conclusions

The accuracy and performance of testing techniques was concluded to be greatly influenced by the design of the air or dye injection probes utilized for specialized test purposes. Injection probes had to be designed for specific purposes such as quick dispersion of injected air or dye while other probes were designed to maintain the injected fluid in a streamline. In order to conduct reliable residence time tests, an injection probe had to be designed to minimize the trail off or bleeding of dye after injection. This was accomplished through the design of a unique bleed tube probe which almost eliminates the trail off of injected dye.

The conclusion arrived at on flow visualization techniques was that to obtain good visual representation of fluid flow the use of the high intensity narrow beam light and air bubble injection is recommended. With proper test conditions and light positioning, valuable information can be obtained.

11.2 Recommendations

In order to obtain a better understanding of the flow phenoma which occur in the ramjet combustor discussed in this report some additional flow measurements would be beneficial. The following is a list of additional experiments which would provide significant information on the flow behavior.

- Use dye injection to determine the location of the dividing streamline between the dome and streamwise flows and the stagnation point location at the top of the combustor duct.

- Vary inlet angle to determine its influence on vortex shedding into the dome, dividing streamline, cycle frequency of helical vortices, and flow separation downstream of the inlet.

- Inject dye along walls to determine the nature of boundary layer behavior, with particular attention directed toward regions of separation and reattachment.

- Determine dome residence time using dye injection.

- Conduct residence time studies of the axial dump combustor for comparisons with the multi-ducted inlet configuration.

- Conduct tests of dome plate fuel injectors for comparisons with hot flow test results.

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